Article

A Method for Calculation of a Hydro Resource Price Using the Operational Features of a Hydropower Plant

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Abstract: The In this paper, a universal method has been developed, which is a combination of an optimization method and a method for assessing the marginal utility. At present, the problem of optimal load distribution in the power system between a hydropower plant (HPP) and thermal power plants (TPP) is solved using the equality of the differential incremental rate characteristics of fuel consumption at TPP and water consumption at HPP by the Lagrangian multiplier method. In this case, the number of iterations can be five or more. The proposed approach is based, first of all, on the correct representation of the differential characteristics and calculation of a hydro resource price for the operational control of the HPP. Based on the comparison of water volume at a HPP and fuel amount at combined heat and power plants (CHPP) used for generation of 1 kW power, it is possible to determine a water price for a HPP. As a result of implementing the developed method for the HPP, a price of sold electricity in the flexible energy market will be comparable with the price for sold electricity produced at CHPPs, being equal to approximately 120 rubles/MW·h.

Keywords: operational control of hydropower plants, optimization, hydro resource price for hydropower plants, incremental water rate characteristic, electricity market, complex criteria of ecological-and-economic efficiency.

1. Introduction

The paper provides the review and development of the method for estimating the price of a hydro resource at a hydropower plant (HPP) during optimization of operating conditions based on complex criteria of ecological-and-economic efficiency under modern conditions [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 combined heat and power plant (CHPP) for generation of 1 kW power [3,4].

2. Choosing a Criterion for Optimizing Operating Conditions of Power Plants and Generating Companies Under Modern Conditions

The administrative system of power engineering management had a significant drawback, which was especially noticeable under market conditions: it was not aimed at making a profit as a general indicator of the work of any department. Commercial performance indicators were replaced by technological ones, for example, such as fulfilling the plan on operating capacity, specific fuel consumption for generation of 1 kWh of electrical energy, maintaining a specified voltage level, etc.

Under modern conditions, according to the profit maximization criterion, a producer will maximize its profit when producing goods at the point where marginal revenue equals marginal costs. 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.

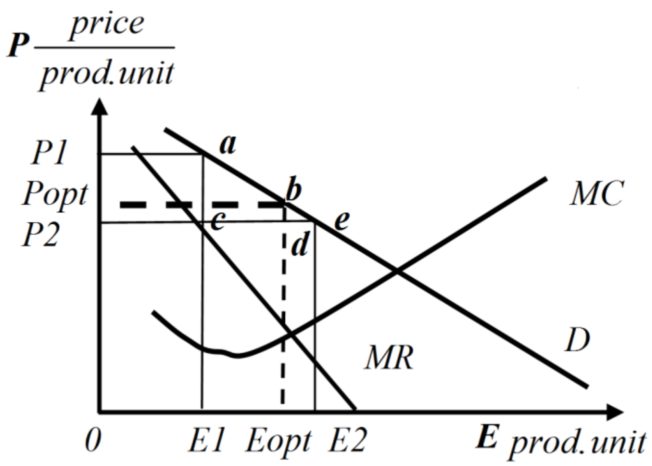

Figure 1. Determination of the optimal production output: D – energy demand for a specified time interval; E_{opt} – optimal output for a specified time interval; P_{opt} – the optimal price at the optimal production output.

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. All these values have the same dimension (price/prod.unit), thus they may be comparable for calculations.

Under modern conditions, each business unit is interested in increasing 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.

3. Model of Functioning Management for Power Plants in the Power System

In this paper, a universal method has been developed, which is a combination of an optimization method and a method for assessing the marginal utility [5,6]. Using this method, it is reasonable to solve the problem of short-term operational optimization of load distribution in hydrothermal power systems.

Consider in detail what is the novelty and the efficiency of the proposed method in comparison with the existing approach.

At present, the problem of optimal load distribution in the power system between the HPP and thermal power plants (TPP) is solved using the equality of the differential incremental rate characteristics of fuel consumption at TPPs and water consumption at the HPP with the use of the Lagrangian multiplier method. Even in the USSR, such characteristics were called the incremental rate characteristics [5,6].

In general, the criterion for the optimal load distribution in the power system without taking into account the technical constraints is as follows:

$$b_1 = b_2 = \ldots = b_n = \lambda q = idem, \qquad (1)$$

where b1 , b2 ,…, bn – incremental fuel rate characteristics at TPPs (n is the number of TPPs in the power system);

q – incremental water rate characteristics at the HPP;

λ – conversion factor, the meaning of which will be considered below.

It should be noted that TPPs are presented in optimization tasks as generating sources with “unlimited energy resources”. This implies that any power of a power plant within the permissible range of its operation at a given moment will be provided with a reserve of energy resource, regardless of the power value carried by the power plant at the previous moment. This gives the reason for combining all thermal power plants into one equivalent TPP (or CHPP), taking into account all the technical constraints.

Hydropower plants belong to generating sources with "limited energy resources", since their amount is determined by the hydrograph of the river and the final useful capacity of the reservoir [7]. This suggests that the HPP power at a given moment depends on the power, with which the HPP operated in the previous time interval. Therefore, the hydropower plants cannot be equivalent, since each of them is unique with the above-considered conditions.

Differential incremental rate characteristics of the HPP and TPPs have different dimensions, namely:

$$b = \frac{dB}{dQ}\ , \tag{2}$$

$$q = \frac{dQ}{dN}, \tag{3}$$

where B – fuel consumption rate (ton of coal equivalent/hour), Q – water flow rate (m^3/s).

Therefore, the coefficient λ in (1) represents a conversion factor being called a measure of the effective use of hydro resources in the power system. Therefore, it is necessary to experimentally select the value of λ taking into account the limited hydro resources at the HPP.

In this case, the number of iterations can be five or more until condition (4) is fulfilled. These circumstances lead to a serious complication of calculations associated primarily with an increase in the number of iterative procedures, solution time, and the convergence of this process [8].

It is assumed that the head does not change at the HPP during the optimization period, although the HPP is being regulated. Such cases are observed for high-head and medium-head HPPs, when the head changes due to pond fluctuations do not have a significant influence on the energy parameters of the power plant. As will be shown below, the assumption of the HPP head constancy considerably simplifies the algorithm for solving the considered problem. At the same time, 1 m^3 of water has almost the same energy for the entire optimization period.

4. The Mathematical Model and the Algorithm for Controlling Operating Conditions of a Mixed Power System

When distributing the total load in the power system consisting of TPPs and a HPP, it is necessary to know the incremental fuel rate characteristics. The influence of the HPP on this distribution is taken into account using the coefficient of energy efficiency of water λ for the HPP, which establishes the relationship between incremental fuel rates at TPPs and incremental water rates at the HPP. The product of the energy efficiency coefficient of the HPP (λ) by its incremental fuel rate is the reduced incremental rate in terms of fuel equivalent for the HPP [9,10].

Therefore, the condition for the efficient joint operation of TPPs and the HPP in the power system is that at each moment they should be operated with the loads corresponding to the equal values of incremental fuel rates at TPPs and reduced incremental rates in terms of fuel equivalent at the HPP. When solving the problem of optimization for a mixed power system, it is necessary to take into account the constraints on a given water flow rate from a HPP reservoir. For this purpose, a water-power calculation is performed, and it is also necessary to select the optimal value of the energy efficiency coefficient λ. The value of the coefficient λ is determined by selection; for the given HPP it is assumed to be constant within 24 hours, depending on the given daily water flow rate.

Compose a mathematical model and an algorithm to achieve the main objective.

Mathematical model:

Objective equation

$$U = \sum_t P_{TPPt} * U_{TPPt} \Rightarrow \min \tag{4}$$

$$U' = \sum_t P_{HPPt} * U_{HPPt} \Rightarrow \min$$
$$U = U + U' \Rightarrow \min$$

Relation equation

$$B_{TPP}(P_{TPP}) \text{ при } Q_{TPP\,min} \le Q_{TPP} \le Q_{TPP\,max} \quad (5)$$
$$Q_{HPP}(P_{HPP}) \text{ при } Q_{HPP\,min} \le Q_{HPP} \le Q_{HPP\,max}$$

Constraint equation

$$P_{TPP\,min} \le P_{TPP} \le P_{TPP\,max} \quad (6)$$
$$P_{HPP\,min} \le P_{HPP} \le P_{HPP\,max}$$
$$P_{HPP} + P_{TPP} - P_S = 0$$
$$\overline{Q}_{av.dailyHPP} = \overline{Q}_{av.giv.HPP}$$

Optimization equation

$$U_{TPPt} = idem \quad (7)$$
$$U_{HPPt} = idem, (\lambda * q = b)$$

where b and q – incremental rate characteristics for water and fuel at the equivalent TPP (CHPP) and the HPP respectively; P_S, N_{TPP}, N_{HPP}, – power system load, values of power served by the equivalent TPP (CHPP) and the HPP respectively; $N_{CHPP\,min}$, $N_{CHPP\,max}$, $N_{HPP\,min}$, $N_{HPP\,max}$,– minimum and maximum power for the equivalent TPP and the HPP respectively:

QGIV – permissible water flow rate at the HPP determined by water-power calculations; λ – the dimension conversion factor.

The condition H = const, which is observed within 24 hours, should be considered separately. At high-head HPPs and the HPP cascade, the downstream changes (in other words, the head changes) is about 1%, since in this case the error for the head fluctuations is approximately 1%, then it can be neglected. In the HPP cascade, the downstream of one station is the upstream of the other. As is known, the upstream changes to a lesser extent when 1 m^3/s of water flows from the upstream to the downstream, since the surface of the upstream is much larger than the downstream [11,12].

At medium-head and low-head HPPs, head fluctuations are more significant than at high-head HPPs.

However, the head at any HPP changes insignificantly during 24 hours.

Therefore, when deriving optimization criteria, most often, the head changes during 24 hours (under operational control) is not taken into account.

The proposed approach is based, first of all, on the correct representation of the differential characteristics (2) and (3). Indeed, these characteristics should be derivatives not from the consumption of energy resources, but from the costs of their use:

$$U_B = P_B B, \quad (8)$$
$$U_Q = P_Q Q, \quad (9)$$

where PB and PQ – the price of fuel at thermal power plants and the price of hydro resource at the HPP respectively.

Then, expressions (2) and (3) will be calculated in the following way:

$$b^* = P_B \frac{dB}{dQ}, \quad (10)$$

$$q^* = P_Q \frac{dQ}{dN}, \quad (11)$$

As for the price of fuel at thermal power plants PB, there are no fundamental difficulties with its calculation. Even in the case of the equivalent thermal power plant, it can be calculated (with some assumptions) as a weighted average price.

It can be said that the problem of evaluating the price of a hydro resource associated with the operating conditions of the HPP in the power system has never been solved. This problem will be focused on in the further presentation of the investigation.

Despite the fact that this task is related to the short-term optimization of operating conditions of power plants in the power system due to the limited energy resources at the HPP, it cannot be solved separately from the optimization of the long-term operating conditions of the power system. In this paper, the short-term optimization implies daily optimization, while the long-term optimization means water-power operating conditions of the HPP throughout the year taking into account the seasonal operating conditions of the HPP [13].

Therefore, the condition of optimal load distribution in a hydrothermal power system can be presented in the new formulation as follows:

$$\begin{gathered} b^* = q^* = idem, \\ H = const, \\ PS = NTPP + NHPP, \\ NTPP\ min \le NTPP \le NTPP\ max, \\ NHPP\ min \le NTPP \le NHPP\ max, \end{gathered} \tag{12}$$

The fundamental differences between the new optimization condition (12) and the previous one (1) are obvious.

Consider them in more detail.

Here b* and q* are determined from (10) and (11) being derivatives of the costs associated with the use of energy resources at TPPs and the HPP, respectively.

There is also no verification in the condition for the requirement that the average daily water flow rate at the HPP is equal to the given flow rate obtained from the water-power calculations in the annual context. This is due to the fact that when plotting incremental rate characteristics for the HPP (q*), the power is considered, with which the HPP will operate in a given period of the year. This means that the flow rate and water head were taken into account. Therefore, the verification for the equality of the average daily water flow rate at the HPP to the given flow rate is redundant. Then, the iterative nature of calculations mentioned above disappears that is the main advantage of the proposed approach.

In addition, there is no verification for λ = const, because the differential characteristics of the costs for the use of energy resources at TPPs (fuel) and the HPP (water) have the same dimension in monetary terms.

And finally, real knowledge appears about the price of a hydro resource, which is used to cover the power balance in the power system.

This makes it possible to use more understandable and correct optimization criteria for optimal load distribution in a hydrothermal power generation system. Moreover, it is valuable and informative to know the price of water resources used for electricity generation at hydropower plants. This gives the possibility to increase the efficiency of management both at the hydropower plant, and in the water utilization system as a whole [14,15].

5. Development of the Methodology for Calculation of a Hydro Resource Price at the HPP

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 harmful impacts on human and 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 rubles) is more expensive at the end of the technological chain, than at the beginning.

To determine a hydro resource price for the operational control of the HPP, the theory of marginal utility can be used [16].

Marginal utility is an increase in total utility when consuming one additional unit of a good (derivative):

$$MU = \frac{\partial U}{\partial Q} \tag{13}$$

where MU – marginal utility, U – utility function, Q – quantity of good consumed.

The principle of marginal utility implies the following: the value of a good of a given kind is determined by the utility of a marginal item that satisfies the least urgent need. Marginal utility determines the demand for a commodity [17,18].

As products, water and fuel are considered in this paper. Their derivatives (i.e., incremental rates of fuel consumption at CHPPs (b) and water flow rate (q) at the HPP) is used as a way to determine the marginal utility calculated by expression (13).

The considerations regarding marginal utility can be presented in a very simple graphical form using the indifference curve (see Figure 2). In this case, according to the rules for plotting indifference curves, it is necessary to derive reciprocals of b and q, i.e. 1/b and 1/q, and put them on X-axis and Y-axis, after that connecting this points by a line (see Figure 2). This line will be the indifference curve.

The reciprocals are derived to show the utility from using the product. For our example, we get 1/b [MW·h/ ton of coal equivalent] and 1/q [MW·h/m3], respectively, that is, in other words, the utility for the consumer of electricity from the use of 1 ton of coal equivalent of fuel and 1 m3 of water, respectively.

There will be 12 such curves for each month of the year, since the HPP is highly maneuverable and dependent on weather conditions, i.e. availability of water resources.

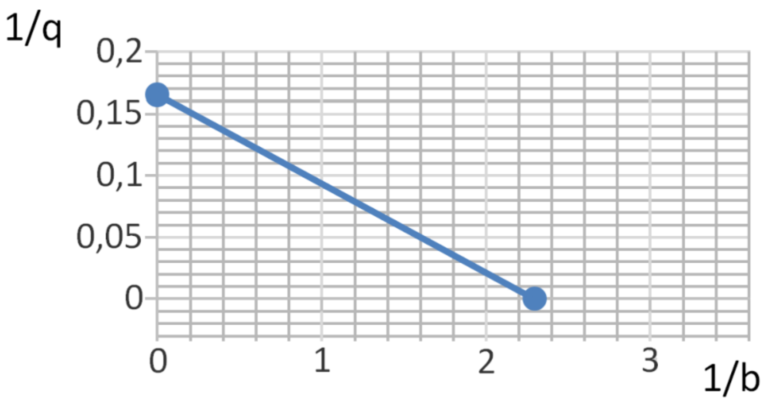

Figure 2. Indifference curve for the natural afflux period (the head of 17.9m).

A mathematical model is composed to determine a hydro resource price for the HPP for optimal coverage of the power system balance.

Then, we get the first objective equation:

$$\frac{1}{b} = \frac{1}{q} \quad \text{at U=const,} \tag{14}$$

where U is the indifference curve.

This can be analyzed using a power engineering example. There is a profit maximization criterion.

To determine the values of b and q used for plotting the indifference curve, we use the results of the water-power calculation, namely the value of N_{guar}. It should be noted that the value of the guaranteed power corresponds to the calculated power security [19]. The guaranteed power is calculated for a low-water year.

Then, the value of Q is determined for the found value of the guaranteed power:

$$N_{GUAR}^{A}(E_{month}) \rightarrow Q, \tag{15}$$

at N_{GUAR} = const.

After that, according to the incremental water rate characteristic, the corresponding value of the incremental water rate (q) can be determined.

$$q = \frac{dQ_{HPP}}{dN_{guar}}.$$

$$Q_{HPP} \geq Q_{guar}.$$

In this case, the balance equations will be as follows:

$$P_S^A = N_{GUAR}^A + N_{TPP}^A \quad (16)$$

Relation equation. During calculations, it is also necessary to take into account the energy balance of the power system.

$$B = f(N_{TPP}),\quad Q_{HPP} = f(N_{HPP}, H_{HPP}).$$

Then, the value of NTPP can be found from (1). In this case, the value of power for the equivalent TPP (CHPP) is calculated as

$$P_S^A - N_{GUAR}^A = N_{TPP}^A \quad (17)$$

From here, it is possible to determine the value of the incremental rate for the equivalent TPP (CHPP). For this purpose, the incremental rate characteristic of fuel consumption of the equivalent CHPP can be used [20].

$$b = \frac{dB}{dN_{TPP}} \quad (18)$$

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.

Using these values, the curve of marginal utility or the indifference curve can be plotted (Figure 2).

Moreover, it should be noted that we obtain a new rule for the transition from the incremental water rate to the incremental fuel consumption without using the Lagrangian multiplier λ. The value of the incremental water rate at the HPP q′ locating on the indifference curve (see Figure 3) will be equal to the corresponding value of the incremental fuel rate at the CHPP b′ locating on the same curve, since water and fuel in this case will have the same importance to the consumer. This is a clear advantage of the methodology when solving optimization problems for mixed power systems consisting of the HPP and TPPs, since it can significantly reduce the computer time (only one action is required instead of five iterations) for solving not only the problem of operational regulation, but also the optimization problem in order to ensure the competitiveness of a generating company in the market.

At the same time, all the corresponding power values for a particular hour according to the daily load schedule are located on this indifference curve within the considered month.

Using the relation equation and knowing the value of Nguar for the HPP, as well as the total capacity of the power system for a specific hour of the day, the power of the equivalent CHPP can be determined using the equality of incremental fuel rate characteristics (Figure 3 and Figure 4).

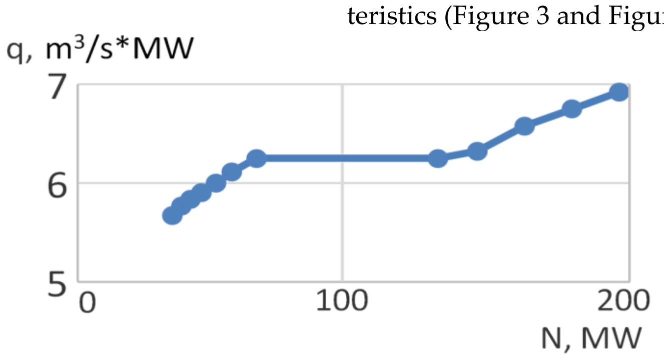

Figure 3. Incremental water rate characteristic for the Novosibirsk HPP with its operation under the head of H=17.9 m.

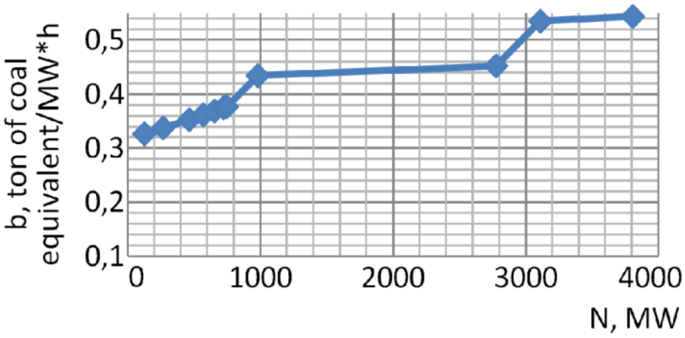

Figure 4. Incremental fuel rate characteristic for the equivalent CHPP with HPP operation under the head of H=17.9 m.

4. In this case, the following constraints should be taken into account:

$$NTPP_{min} \le NTPP \le NTPP_{max},$$
$$NHPP_{min} \le NTPP \le NHPP_{max}, \quad (19)$$

5. Then, the optimization equation MR=MC should be derived [21]. This is the profit maximization criterion. In this case, a producer will maximize its profit when producing goods at the point where marginal revenue equals marginal costs. This leading principle of profit maximization is called as the rule of equality between marginal revenue and marginal costs.

At the same time, in order to obtain a curve of marginal costs, it is necessary to determine the price of a hydro resource, taking into account the forced operating conditions of the HPP based on the complex criterion of ecological and economic efficiency.

For this purpose, the following procedure should be performed.

Using the indifference curve for marginal costs of water and fuel consumption, it should be noted that the slope of the indifference curve (α) remains exactly the same as given in Figure 3.

Hence, the hydro resource price for a HPP can be determined using the diagram given in Figure 5, where the indifference curve for marginal costs at the HPP and TPPs is shown.

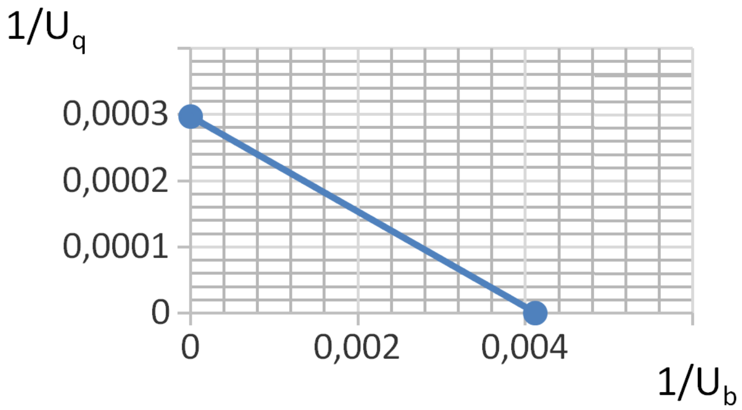

Figure 5. The indifference curve for marginal costs in the period of operation with natural river flow (the head is 17.9m).

Then, a hydro resource price for a HPP can be calculated using the following expression:

$$U_q = p * q, \quad tg\alpha = \frac{1/q}{1/b}, \quad p_w = tg\alpha * \frac{U_B}{p_f}. \qquad (20)$$

where Uq – marginal costs at the HPP, Ub – marginal costs at the CHPP, b – incremental fuel rate at the CHPP, q – incremental water rate at the HPP, p_w – water price for the HPP, p_f – fuel price for the equivalent CHPP.

Using the example of the natural afflux period, a HPP water price can be determined in the following way: $p_w = \frac{U_b}{tg\alpha * q} = \frac{242.5}{0.072 * 6.05 * 3600} = 0.1545 \frac{rubles}{m^3/s}$. To convert water price into [rubles/MW·h], it is necessary to determine the HPP marginal costs for generation of the guaranteed power, or, in other words, to form the proportion $U_q = U_b / tg\alpha$ =242.5/0.072=3364.97 rubles/MW·h=3.35 rubles/kW·h. This is a hydro resource price obtained using the technological features of the HPP.

Then, the marginal costs for the HPP will be determined as

$$MC = p_w * q. \qquad (21)$$

As an example, marginal costs for the Novosibirsk HPP and the equivalent CHPP are given in Figure 6 and Figure 7.

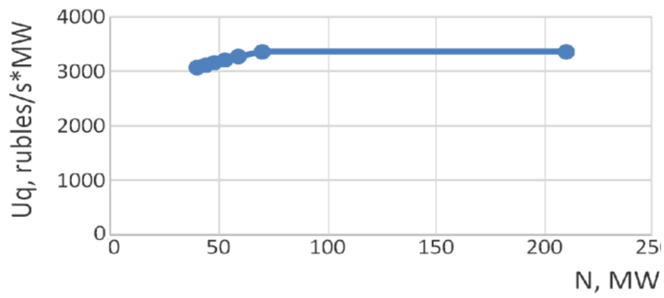

Figure 6. Marginal costs characteristic for the Novosibirsk HPP with its operation under the head of H=17.9 m.

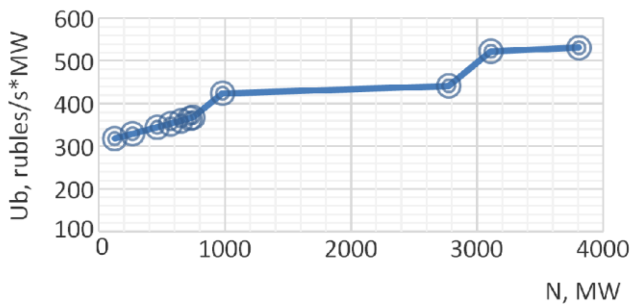

Figure 7. Marginal costs characteristic for the equivalent CHPP with HPP operation under the head of H=17.9 m.

Solving the system of equations describing curves of marginal costs and marginal revenue, optimal values of average monthly energy output (E_{opt}) for every season and average daily power can be determined:

$$N_{opt} = E_{opt} / t_{month}, \tag{22}$$

where tmonth – average number of hours in a month (720 hours).

To determine optimal load conditions for the Novosibirsk HPP in each period of the year, the profit maximization criterion was used (see Table 1).

Table 1. Optimal values of power output for the Novosibirsk HPP by year seasons.

Season	**HPP operation with the head of H=14.05m**	**HPP operation with the head of H=17.5m**	**HPP operation with the head of H=17.9m**
Profit rate	0%	0%	0%
Power, MW	305	70	124
Electric energy, MW·h	219600	50400	89280
Posted price, rubles/MW·h	3600	3786	3700
Revenue, rubles	2371680000	1335700800	660672000

Practical testing of the developed method at the Novosibirsk HPP resulted in obtaining the following water prices for the HPP by year seasons (high water, low water, and operation with natural river flow): the water price for the Novosibirsk HPP in the high-water period is 0.1124 rubles/m³/s, in the low-water period – 0.1583 rubles/m³/s, with natural river flow – 0.1545 rubles/m³/s.

Moreover, it should be noted that the water price at the Novosibirsk HPP is comparable to the fuel price at the CHPP that indicates the correctness of the calculations.

For example, the water price at the Novosibirsk HPP for the drawdown period is 0.1583 rubles/m³/s. When converting into hours, we get 0.1583*3600 = 569 rubles/m³ that is comparable to the price of 1 ton of brown coal, being equal to 690...980 rubles per ton depending on the year season. If the similar indicators are calculated for the Kuznetsk coal used at CHPPs, then we get 0.1583*3600 = 569 rubles/m³ for the drawdown period at the Novosibirsk HPP that is the almost half of the price of 1 ton of the Kuznetsk coal, being equal to 1200 rubles per ton. This demonstrates the efficiency of the developed methodology, because it will allow loading a cost-effective and environmentally friendly HPP instead of thermal power plants.

6. Discussion

When compared with the Lagrangian multiplier method, the developed methodology significantly reduces the number of iterations and the computer time for solving the problem (one iteration versus five iterations in the Lagrangian multiplier method).

Then, the correctness of the developed methodology was checked by comparing the results obtained for the most favorable load distribution of a mixed power system between the equivalent CHPP and the HPP according to the method proposed by the authors and the conventionally used Lagrangian multiplier method.

According to the conventional Lagrangian multiplier method, the following load distribution in the power system between the equivalent CHPP and the Novosibirsk HPP is obtained for the period of filling (Figure 8).

In this case, it should be noted that the deviation error of the average daily flow rate Qav.daily from its given value Qgiv according to this method was 4%, or 2676.7 m3/s versus 2767 m^3/s for the filling period.

For the methodology developed by the authors, the following results can be presented (Figure 9).

Moreover, it should be noted that the deviation error of Qav.daily from Qgiv according to the proposed method was 9%, or 3033 m^3/s versus 2767 m^3/s for the filling period. At the same time, the share of the Novosibirsk HPP in covering the daily load schedule increased by 12%.

Therefore, the results obtained by the developed method are within the range according to the conventional method of load distribution in the mixed power system, i.e. the Lagrangian multiplier method. This indicates the reliability of the results obtained and the correctness of the developed approach.

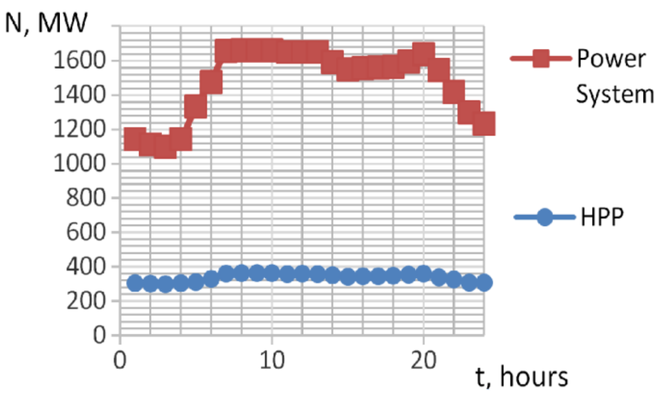

Figure 8. Load distribution in the mixed power system by the Lagrangian multiplier method for the period of filling.

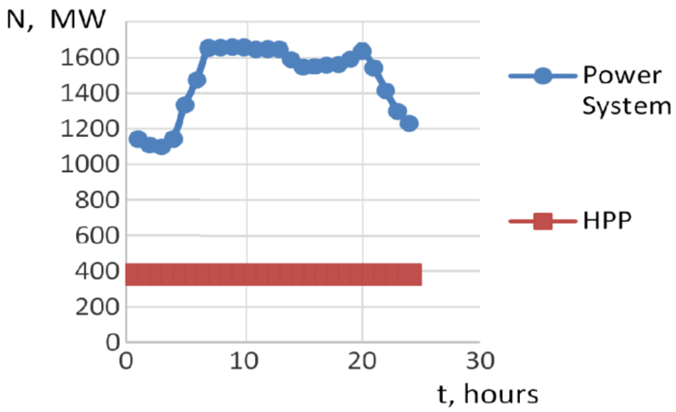

Figure 9. Load distribution in the mixed power system by the marginal utility method for the period of filling.

7. Conclusion

As a result of the performed investigation, the following conclusions can be made:

- the critical analysis of existing criteria for power plant management was carried out;
- the conventional methodology of the most favorable load distribution in a hydrothermal power system using the Lagrangian multiplier method was analyzed, and the drawbacks associated with the multiplicity of iterations and the process duration were revealed. The condition H = const, which is observed within 24 hours, should be considered separately. At high-head HPPs and the HPP cascade, the downstream changes (in other words, the head changes) is about 1%, since in this case the error for the head fluctuations is approximately 1%, then it can be neglected. In the HPP cascades, the downstream of one station is the upstream of the other. As is known, the upstream changes to a lesser extent when 1 m^3/s of water flows from the upstream to the downstream, since the surface of the upstream is much

larger than the downstream. At medium-head and low-head HPPs, head fluctuations are more significant than at high-head HPPs. However, the head at any HPP changes insignificantly during 24 hours. Therefore, when deriving optimization criteria, most often, the head changes during 24 hours (under operational control) are not taken into account. The assumption of the HPP head constancy considerably simplifies the algorithm for solving the problem;

- the proposed approach is based, first of all, on the correct representation of the differential characteristics of the HPP and the equivalent CHPP. Indeed, these characteristics should be derivatives not from the consumption of energy resources, but from the costs of their use. This is a clear advantage of the methodology when solving optimization problems for hydrothermal power systems consisting of the HPP and the equivalent CHPP, since it allows taking into account all the operating features of the HPP and significantly reducing the computer time (only one action is required instead of several iterations) for solving not only the problem of operational regulation, but also the optimization problem in order to ensure the competitiveness of a generating company in the market. At the same time, all the corresponding power values for a particular hour according to the daily load schedule are located on this indifference curve within the considered month.
- the use of the theory of marginal utility was substantiated that can be used to determine the hydro resource price taking into account the operating features of the HPP for optimal coverage of the power system balance and that has never been studied before;
- proposed approaches and methods were verified and validated mathematically and experimentally. The general statements of the methodology were realized for the specific power facilities, the results of which revealed an increase in the share of the HPP in covering the daily load schedule of about 12%.

8. Patents

Authors have patent resulting from the work reported in this manuscript: Patent for invention number 2647241, class F24D 10/00 F01K 17/02 F24D 19/10 "Method of fuel costs separation at CHP".

Author Contributions: Conceptualization, Yuri A. Sekretarev and Tatiana V. Myateg; methodology, Yuri A. Sekretarev and Tatiana V. Myateg; software, Tatiana V. Myateg; validation, Yuri A. Sekretarev; formal analysis, Yuri A. Sekretarev and Tatiana V. Myateg.; investigation, Yuri A. Sekretarev and Tatiana V. Myateg; resources, Yuri A. Sekretarev and Tatiana V. Myateg; data curation, Yuri A. Sekretarev; writing—original draft preparation, Yuri A. Sekretarev, Tatiana V. Myateg and Olga S. Atamanova; writing—review and editing, Yuri A. Sekretarev and Olga S. Atamanova; visualization, X.X.; supervision, X.X.; project administration, X.X.; funding acquisition, Y.Y.

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