Modeling the Angara-Yenisei Cascade Operations Based on Firm Winter Power Output Maximization

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***Abstract* — The study explores the current challenges and constraints in regulating the operations of the Angara-Yenisei cascade of hydroelectric power plants. An overview of modern approaches to hydropower plant operation modeling is provided. A mathematical formulation of maximizing of the firm winter power output of the Angara-Yenisei cascade is presented. The developed Garant-Cascade system is described highlighting the interaction of its primary modules. The Angara-Yenisei cascade operations and optimal firm winter power output under various scenarios and constraints were calculated using the Garant-Cascade system. A database of average monthly reservoir inflows for the 1903–2025 period served as the input data for modeling a continuous series of hydropower operating conditions. Two scenarios of the cascade operations with and without firm winter power were discussed. The first scenario involves maintaining the required cascade winter power by regulating discharge at the Bratsk hydropower plant. The second scenario utilizes the dispatch curve to set the discharge of the Bratsk hydropower plant according to the current reservoir water level. The five levels of the winter power (low, reduced, firm, increased, high) were identified depending on the reservoir water level at the beginning of the winter period. The modeling results for the hydropower plant operations during the extreme low-water period of 2014–2018 are presented, demonstrating the minimum cascade winter power.**

***Index Terms* — Hydropower plant, operations, modeling, exceedance probability, water management rules, low-water periods, reliability.**

I. Introduction

The Angara-Yenisei cascade (AYC) includes seven large-scale hydropower plants with an installed capacity of 24.8 GW and serves as the primary regulator of the power balance and electricity generation within the interconnected power system of Siberia [1, 2]. The AYC operation depends largely on natural factors [3], primarily the water inflow into reservoirs, as well as the requirements of both water management and power systems. The occurrence of extreme low-water years and prolonged low-water periods is of particular interest when assessing the operational reliability of the cascade, especially for winter season when there is an increased demand for electricity.

Given the long-term and seasonal variability of the flow in the Angara and Yenisei basins, the AYC operation depends on the water storage volumes in long-term storage reservoirs. The primary regulators within the AYC are located in the Angara cascade, specifically in the Irkutsk (Lake Baikal) and Bratsk reservoirs. At present, their reserves are significantly limited compared to the design parameters [4–6]. Due to stringent environmental constraints regarding Lake Baikal, the Irkutsk hydropower plant (HPP) operates under seasonal regulation protocols. In 2001, the permissible regulation range for the Lake Baikal water level was reduced to one meter, representing 50% of its natural flow. At present, several water intakes and berths at the Bratsk reservoir are located at an elevation

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of 394.73 m BHS (Baltic Height System), while the dead storage level is 391.73 m BHS, reducing the active storage capacity by 30%.

Another issue is that the current water management rules (WMR) for the AYC reservoirs are irrelevant. The regulations for the Angara cascade were developed in 1988 [7] under different socio-economic conditions. They failed to meet the needs of various water users within the water management system, as priority was given solely to power generation. Based on the WMRs, the AYC control system was developed to manage the reservoir cascade as a unified energy source operating under inter-basin electrical compensation regulation [2]. The 1988 WMRs established a firm winter power output of 9 800 MW for the AYC (excluding the Boguchany HPP), provided by the Irkutsk (Lake Baikal) and Bratsk reservoir storage volumes.

Therefore, the reduction in the live storage of the two primary cascade reservoirs increased the risks of low-water periods, which were originally taken into account in the plant design specifications. These risks led to a decline in the overall reliability and stability of both the power and the water management systems. The commissioning of the Boguchany HPP, changes in technical characteristics of the reservoirs, stricter environmental requirements, and hydrological shifts (such as the extreme low-water period of 2014–2018) necessitate the re-evaluation of the current firm winter power output for the AYC. To this end, specialized approaches and tools must be developed to analyze the cascade operations under current constraints.

II. Overview of Modern Approaches for Modeling Hydropower Plant Operations

In countries with a high share of hydropower, such as Brazil, China, Canada, and Norway, firm power output of an HPP is determined considering numerous factors, including hydrological uncertainty, as well as market and environmental constraints. In the last decade, stochastic dual dynamic programming (SDDP) has emerged as an effective method for long-term operational planning. This approach is implemented in tools such as the Brazilian NEWAVE model, which optimizes power allocation between HPPs and TPPs based on thousands of hydrological scenarios [8, 9]. Similar SDDP models are applied in Norway, Latin American countries, and China for reservoir cascade management [10, 11]. However, SDDP models are primarily effective for convex optimization problems and do not meet the stringent operational or environmental requirements. To address these issues, metaheuristic approaches such as genetic algorithms (GA, NSGA-II), swarm methods (PSO, GWO), and their hybrids (A-DEPSO, HB-SA) are utilized to balance the generation, environmental requirements, and reliability [12].

Commercial software systems such as DESSEM, PLEXOS, and RiverWare are employed for short-term HPP operational planning [13, 14]. The fully open-source SpineOpt model is successfully applied to analyze the Nordic power system, involving thousands of HPPs [15]. In resource-constrained countries such as Kenya, Colombia, Nepal, and Pakistan, the water evaluation and planning system (WEAP) model is widely used to assess the impacts of climate change and competing water use on hydropower potential [16–18]. The models differ in their priorities for water resource allocation: water-oriented models (WEAP, HEC-ResSim) primarily factor in water management and environmental constraints, as well as water user requirements, whereas energy-oriented models (PLEXOS, OSeMOSYS) target the maximization of energy indicators, which may lead to the violation of requirements for some water users [16].

Managing the risks of low-water periods is essential for systems with a high hydropower penetration. For example, following the 2021 drought in Brazil (the most severe in 90 years), regulators were forced to revise the HPP operational planning methodology. The calculation of firm power output has evolved to incorporate not only mean values but also risk-oriented metrics, such as the conditional value-at-risk (CVaR) for 5% of the worst hydrological scenarios [9]. Such changes highlight the necessity of transitioning to integrated models that link water management and power systems [19, 20].

Promising directions for enhancing HPP operational planning include the development of digital twins for water management and power systems, combined with mathematical programming methods, including stochastic models [10, 21, 22].

III. Maximization of Firm Winter Power Output of the Angara-Yenisei Cascade

The key indicator of the AYC operation management is the total cascade power output during the winter period, when electricity demand increases. This indicator factors in the number of deficit years and the allowable power reduction during low-water periods. In summer, the cascade replenishes its reservoirs, while meeting water management and environmental requirements (primarily for Lake Baikal) and ensuring navigation releases to the Lower Angara and the Yenisei. In winter, the priority shifts to power generation, specifically, the firm power output.

We propose formulating the calculation of the firm winter power output of the cascade as a joint multi-objective optimization problem based on two criteria:

1. Maximizing the firm winter power output while complying with the allowable number of deficit or reliable years;
2. Minimizing the firm winter power output reduction during deficit years.

The cascades of the *AYC* and their respective HPPs are indicated as follows: *AC* – the Angara cascade (*Ir* – Irkutsk, *Br* – Bratsk, *Ui* – Ust-Ilimsk, *Bg* – Boguchany) and *YC* – the Yenisei cascade (*Ssh* – Sayano-Shushenskaya, *Mn* – Mainskaya, *Kr* – Krasnoyarsk). To study the operating conditions within the framework of the 1988 WMR, an additional limited AYC^{-} is considered, which excludes the Boguchany HPP.

The list of studied HPPs categorized by group is as follows:

$$\Gamma = \left\{ \Gamma^{AC}, \Gamma^{YC}, \Gamma^{AYC}, \Gamma^{AYC^{-}} \right\},$$

$$\Gamma^{AC} = \left\{ Ir, Br, Ui, Bg \right\},$$

$$\Gamma^{YC} = \left\{ Ssh, Mn, Kr \right\},$$

$$\Gamma^{AYC} = \left\{ Ir, Br, Ui, Bg, Ssh, Mn, Kr \right\},$$

$$\Gamma^{AYC^{-}} = \left\{ Ir, Br, Ui, Ssh, Mn, Kr \right\},$$

where ν is the HPP group index, and γ is the individual HPP index.

The considered period is limited to a set of years $T = \{t_k : k = \overline{1,n}\}$, based on accumulated inflow statistics for the reservoirs.

The power of the γ-th HPP is defined as $W^{\gamma}(t,\tau)$, where t is the hydrological year index and τ is the month of the hydrological year. The hydrological year runs from May of the current calendar year to April of the following year: $\tau \in \{5,...,12,1,...,4\}$. The winter period spans from November to March: $\tau^{\eta} \in T^{\eta}(t) = \{11,...,12,1,...,3\}$.

The power of the ν-th HPP group $\Omega^{\nu}(t,\tau^{\eta})$ is determined for each year and month of the winter period:

$$\Omega^{\nu}(t,\tau^{\eta}) = \sum_{\gamma\in\nu} W^{\gamma}(t,\tau^{\eta}). \tag{1}$$

We define $\Omega^{\nu}_{\beta}(t)$ as the firm winter power output of the ν-th HPP group for each time period $t \in T^{\beta}$, where β is an indicator of firm winter power compliance.

The set of years meeting the firm winter power output is as follows:

$$T^{\beta} = \left\{ t_k : \Omega^{\nu}_{\beta}(t_k) \ge \Omega^{\nu}_{0} \right\},\ T^{\beta} \subseteq T. \tag{2}$$

The set of years with reduced winter power output is as follows:

$$T^{\lambda} = \left\{ t_k : \Omega^{\nu}_{\beta}(t_k) < \Omega^{\nu}_{0} \right\},\ T^{\lambda} \cup T^{\beta} = T, \tag{3}$$

where Ω^{ν}_{0} is the firm winter power output maintained throughout the entire period T^{β}, λ is an indicator of reduced winter power.

The winter power exceedance probability μ is defined as the ratio of the number of years the firm winter power output was met to the number of years from the accumulated statistics:

$$\mu = \frac{|T^{\beta}|}{|T|+1}. \tag{4}$$

The following basic constraints must be satisfied when regulating HPP operations:

– upper and lower bounds of the reservoir headwater level:

$$H^{\gamma}_{1}(\tau) \le H^{\gamma}(t,\tau) \le H^{\gamma}_{2}(\tau), \tag{5}$$

where H^{γ}_{1} is the dead storage level, H^{γ}_{2} is the full reservoir level of the γ-th HPP;

– flow rate:

$$Q^{\gamma}_{1}(\tau) \le Q^{\gamma}(t,\tau) \le Q^{\gamma}_{2}(\tau), \tag{6}$$

where Q^{γ}_{1} is the minimum (environmental) flow rate, Q^{γ}_{2} is the maximum flow rate of the γ-th HPP, including turbine discharge and spillway discharge.

Additional constraints are also imposed on the downstream pool level, the allowable hydraulic head, and turbine discharge, given varying loads of units and their maintenance (omitted in this paper).

The regulatory exceedance probability limits can be defined as:

$$\underline{\mu} \le \mu \le \overline{\mu}. \tag{7}$$

A minimax approach is employed to estimate the firm winter power output. The minimum winter power output for each ν-th HPP group is determined as:

$$\Omega^{\nu}(t) = \min\left\{ \Omega^{\nu}_{\beta}(t,\tau^{\eta}) : \tau^{\eta} \in T^{\eta}(t) \right\}. \tag{8}$$

For the set of years meeting condition (2), the firm

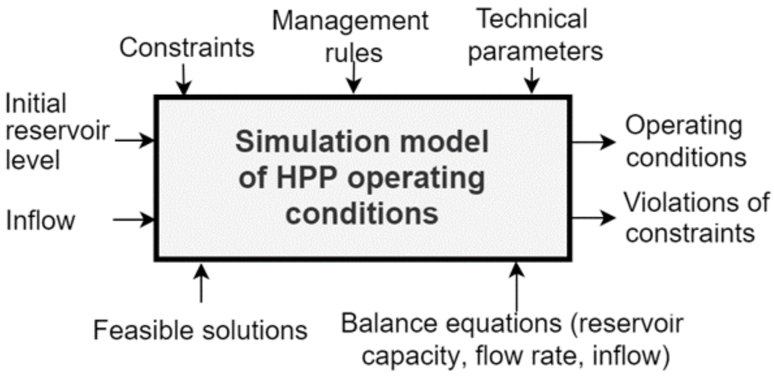

Fig. 1. Structure of the HPP operation simulation model (IDEF0 notation).

winter power output is defined as follows:

$$\bar{\Omega}^{\nu}_{\beta} = \max\left\{\Omega^{\nu}_{\beta}\left(t\right): t \in T^{\beta}\right\}, \tag{9}$$

where $\bar{\Omega}^{\nu}_{\beta}$ is the maximum firm winter power output for all years meeting conditions (2) and (7).

If firm winter power output is not met, it is necessary to determine the minimum magnitude of its reduction:

$$\Omega^{\nu}_{\lambda}\left(t\right) = \min\left\{\Omega^{\nu}_{\lambda}\left(t, \tau^{\eta}\right): \tau^{\eta} \in T^{\eta}\left(t\right)\right\}, \tag{10}$$

$$\bar{\Omega}^{\nu}_{\lambda} = \max\left\{\Omega^{\nu}_{\lambda}\left(t\right): t \in T^{\lambda}\right\},$$

where $\bar{\Omega}^{\nu}_{\lambda}$ is the maximum winter power output during deficit years that meet conditions (3).

Excluding additional constraints, this problem may be formulated as a mathematical programming model, with monthly water flow rates for each HPP throughout the study period. Given the nonlinearities in hydraulic characteristics (reservoir levels depend on storage volumes, upstream and downstream pool levels depend on HPP discharges, backwater of downstream reservoirs, and others) alongside the complex operational curves of hydro units, this problem formulation precludes the use of standard mathematical programming methods, such as quadratic or convex programming. An effective approach to solve it is to combine linear and dynamic programming methods to find a feasible near-optimal solution, which is then refined to achieve the desired accuracy.

IV. System for Modeling Cascade Firm Winter Power Output

To model the AYC HPP operations, a system of models [23–25] was developed at the Melentiev Energy Systems Institute (ESI SB RAS). This system integrates various simulation, optimization, and stochastic models into a unified software package, enabling the study of HPP operation management within water management and power systems under diverse constraints. Furthermore, it formulates proposals for mid- and long-term operations to

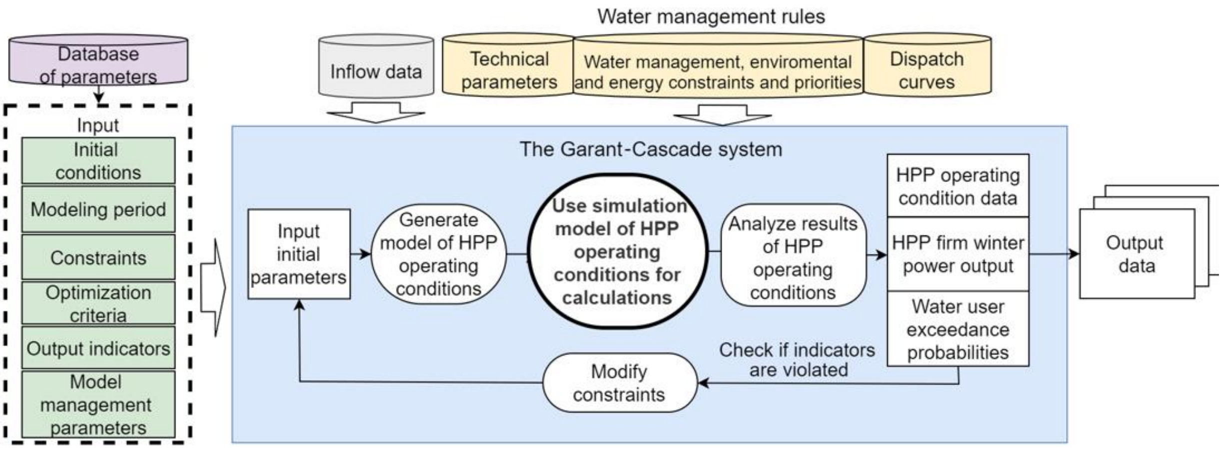

Fig. 2. Core modules of the Garant-Cascade system.

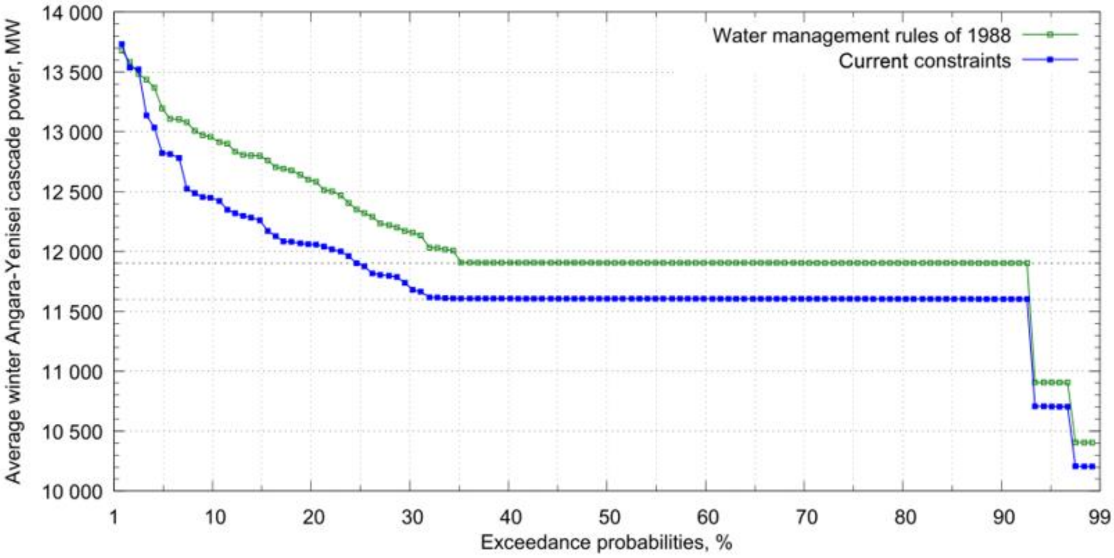

Fig. 3. Exceedance probabilities of the AYC minimum winter power: current constraints versus 1988 WMR.

enhance system resilience, reliability, and efficiency in both planning and management.

The developed components were employed to implement the Garant-Cascade software system. It models HPP cascade operations, assesses the exceedance probability of energy indicators (including firm winter power output) and water management requirements under various constraints.

The core of the Garant-Cascade system is a simulation model for calculating HPP operations, as shown in Figure 1. Its inputs include the initial reservoir levels at the beginning of the study period and water inflows to each reservoir at a specified time step (a month, a ten-day period, or a day). The outputs comprise operational data (HPP flow rates, power, and upstream and downstream pool levels, and others). Using various methods, the simulation model identifies feasible solutions based on predefined management rules, technical parameters, and constraints. In the absence of a feasible solution, the system generates output data specifying the type of violation.

The module for a result analysis generates statistics for all calculated indicators, which are then used to determine the firm winter power output and the magnitude of its forced curtailment during low-water periods. During high-water periods, increased winter power is calculated to minimize spillway discharge. If constraints are violated, the model parameters are adjusted, and new calculations are performed until the optimal operating conditions are achieved based on the specified criteria. The output reports contain all necessary information, including tables and charts of the studied operations.

V. Modeling Results for the Angara-Yenisei Cascade Operations

The developed Garant-Cascade system was employed to perform numerous calculations to identify the optimal firm winter power output of the AYC under various operating scenarios. A database of average monthly water inflows to the reservoirs for the timeframe from 1903 to 2025 was used to model a long-term continuous series of the cascade operations. The operating conditions of the Sayano-Shushenskaya and Krasnoyarsk HPPs were determined in accordance with their dispatch curves. The operating scenarios for the Irkutsk HPP were determined based on a dispatch curve incorporating various parameters, including Lake Baikal water level ranges, environmentally sensitive zones, navigation and water intake requirements, and pre-flood drawdown targets. The operating conditions of the Bratsk HPP ensured the required firm power output of the cascade during the winter period and the navigation flow rate during the summer.

Figure 3 presents the modeling results for the continuous long-term series of HPP operations, showing the annual exceedance probabilities of the AYC winter power output for two scenarios: 1) current constraints (with the minimum water level of the Bratsk reservoir at 394.73 m BHS; 2) the 1988 WMR for the cascade, including the Boguchany HPP. Under current constraints, the AYC firm

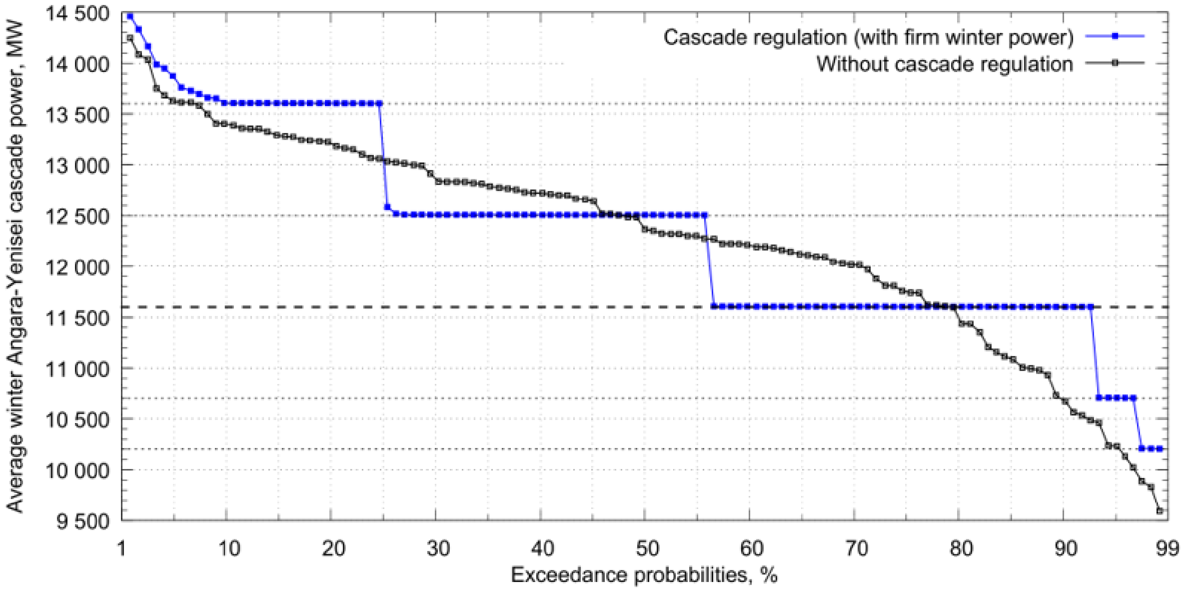

Fig. 4. Exceedance probabilities for the average winter power of AYC with and without cascade regulation.

winter power output is reduced by 300 MW. There is also a 200 MW decline in winter power output during deficit low-water years.

Figure 4 shows the exceedance probability curves for the average AYC winter power, both with and without cascade regulation. Under the cascade regulation, five winter power levels were defined (low, reduced, firm, increased, and high) based on AYC reservoirs volumes as of November 1. Under the non-cascade regulation, the winter flow rates of the Bratsk HPP were determined by its dispatch curve based on the current reservoir water level.

Under the cascade regulation, the AYC firm winter power output of 11 600 MW is achieved with 93% exceedance probability. Without the cascade regulation, this parameter is maintained with only 80% exceedance probability.

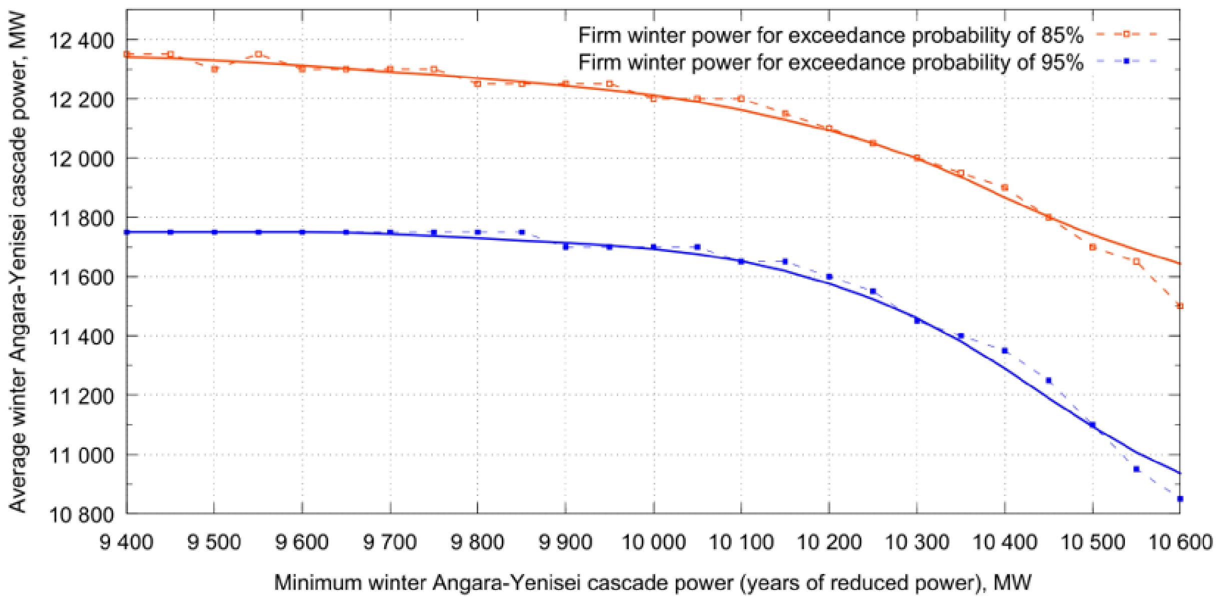

Fig. 5. Range of variations in the AYC firm winter power output for exceedance probabilities of 85% and 95%, under the minimum winter power constraint.

TABLE 1. Average Winter Power of the AYC, MW, and its Proportion Relative to the 11 600 MW Firm Power Output During the 2014–2018 Low-Water Period, Under the Target Minimum Reservoir Level of the Bratsk HPP of 394.73 m BHS

Hydrological year	Lake Baikal water levels, m PHS** (May 1 – Nov. 1)	Initial reservoir level of the Bratsk hydropower plant on May 1, 2014, m BHS						
		394.73	395.73	396.73	397.73	398.73	399.73	400.23
2014	456.15–456.47	8 550* (74%)	9 250 (80%)	9 700 (84%)	9 900 (85%)	10 400 (90%)	11 200 (97%)	11 600 (100%)
2015	455.93–456.26	9 600 (83%)	9 650 (83%)	9 700 (84%)	9 900 (85%)	10 000 (86%)	10 000 (86%)	10 000 (86%)
2016	455.77–456.43	9 650 (83%)	9 650 (83%)	9 700 (84%)	9 900 (85%)	10 000 (86%)	10 000 (86%)	10 000 (86%)
2017	455.97–456.28	9 650 (83%)	9 650 (83%)	9 700 (84%)	9 900 (85%)	10 000 (86%)	10 000 (86%)	10 000 (86%)
2018	455.82–456.85	10 700 (92%)	10 700 (92%)	10 700 (92%)	11 600 (100%)	11 600 (100%)	11 600 (100%)	11 600 (100%)

* When the Bratsk reservoir level decreases to 394.62 m.
** PHS is Pacific Height System; BHS is Baltic Height System.

Optimization calculations were performed to determine the maximum firm winter power output across the regulatory exceedance probability range of 85–95% and various allowable magnitudes of its reduction over the study period (Fig. 5). At an 85% exceedance probability, the firm winter power output can be increased by 500–600 MW compared to the scenario with 95% exceedance probability.

The AYC operations face the primary risk during prolonged low-water periods, particularly when they concurrently occur across several large basins, such as Lake Baikal and the Bratsk reservoir (as observed in 2014–2018). Table 1 summarizes the reductions in the cascade minimum winter power under various initial water levels of the Bratsk reservoir at the beginning of a low-water period.

With the initial Bratsk reservoir level at 394.73 m, the most severe operating scenario occurred in 2014. The winter power dropped to 74% of its firm value. Under these conditions, the minimum reservoir level declined to 394.62 m (11 cm below the permissible level) due to the environmental flow rate requirements at the Ust-Ilimsk HPP. A minimum winter power of 10 000 MW was achieved only under an initial reservoir level of 398.73 m. In the historical series, the minimum winter power was as high as 10 200 MW due to favorable hydrological conditions before 2014.

In the current context, the requirements of HPPs as water users must be met following the reliability and exceedance probability standards within the 85–95% range. Large cascades such as the AYC should target the upper range of an exceedance probability. Given the risks of prolonged low-water periods, it is essential to establish a trade-off between the cascade winter power (efficiency) and its exceedance probability (reliability), and to plan reserve power for thermal power plants.

It is worth noting that this study evaluates the AYC operations based on current regulation rules, excluding additional measures to enhance firm winter power output, such as summer navigation drawdown of the Ust-Ilimsk and Boguchany reservoirs.

VI. CONCLUSION

The study established the updated indicators for the AYC firm winter power output, defined by its exceedance probability (reliability). Regulation of the HPP cascade operations without inter-cascade regulation can enhance energy indicators in certain years through the development of more efficient dispatch curves for individual HPPs. However, the overall reliability of the cascade operation decreases during extreme low-water periods that occur simultaneously across different basins. In the inter-cascade regulation scenario, the AYC demonstrates substantial potential for boosting the operational stability of both power and water management systems.

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