Multi-time-scale nested optimal scheduling model for cascaded hydropower reservoirs

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Abstract. As more hydropower plants are in operation, it is difficult to balance the medium- and long-term benefits with the short-term benefits when developing an optimal scheme for power generation from cascaded hydropower reservoirs. And traditional models have difficulty making full use of the latest runoff forecast information. To overcome these problems, a multi-time-scale nested optimal scheduling model for cascaded hydropower reservoirs is developed. This model analyzes the level-by-level control strategy and rolling update mechanism between upper and lower level submodels. An efficient algorithm for solving the model is also given. In this study, the model is applied to four cascaded hydropower reservoirs located at the Yangtze River. The case study shows that the developed model can better coordinate the medium- and long-term benefits with the short-term benefits, make full use of the latest forecast information, and enhance the power generation efficiency of the cascaded hydropower reservoirs. Compared with the results of the existing scheduling model, the total power generation from the proposed model is improved under the same boundary conditions.

1. Introduction
The development and utilization of hydro energy resources in China are developing rapidly, and the cascaded reservoir groups in each basin are gradually formed [1]. It is the key for power generation enterprises to improve their competitiveness by making full use of cascaded reservoirs hydro energy resources, carrying out research on joint scheduling of reservoir groups, and improving the overall power generation benefits [2]. In recent years, there has been increasing research effort in the optimal scheduling of cascaded hydropower reservoirs [3]. However, such studies are based on deterministic incoming water processes and cannot deal with the incoming water uncertainties in the scheduling process. To study the uncertainty in the optimal scheduling of a group of reservoirs, stochastic optimization of cascaded hydropower reservoirs is introduced [4][5]. By treating the incoming runoff process as a stochastic process, the optimal scheduling of cascaded hydropower reservoirs can be summarized as a multistage Markov decision process to establish a stochastic scheduling model. Nevertheless, this method has the problem of "dimensional disaster". The stochastic optimization model for cascaded hydropower reservoirs considers the uncertainties in dispatching, but when considering the long-term runoff change pattern, it cannot take into account the changing runoff information and ignores the value of runoff forecasting. Power generation enterprises should balance the long-term benefits with short-term benefits and play the role of long-term guidance to short-term. At the same time, the information provided by short-term data has important practical significance.
forecasts should be fully utilized to continuously update the short-term schedule on a rolling basis. The multi-time-scale nested optimal scheduling model for cascaded hydropower reservoirs is adopted to solve these problems. This model designs the submodels in different levels according to the difference in the accuracy of the forecast information. These submodels have various scheduling scales appropriate to the forecast scales for different scheduling periods. Furthermore, the submodels in each level are nested, making use of the constantly changing forecast information for continuous optimization, real-time adjustment, and rolling decisions. In this paper, the model is introduced to study and solve the optimal dispatching problem of four cascaded hydropower reservoirs (namely, Xiluodu, Xiangjiaba, Three Gorges, and Gezhouba) located at the Yangtze River. Compared with the existing scheduling model, the developed model has a better performance in coordinating the combined benefits of the period faced and the residual period.

2. Methods

2.1. Nested submodel division
In the multi-time-scale nested optimal scheduling model, the water level calculation results of the upper submodel are used as the initial and final water level control of the lower submodel. This method improves the guidance significance of medium- and long-term optimal scheduling to short-term optimal scheduling, thus coordinating long-term and short-term benefits. According to the actual scheduling needs of the cascaded hydropower reservoirs and the accuracy of the incoming runoff forecast, the study divides the optimal scheduling model into a three-level nested structure (see figure 1).

Figure 1. Nested submodel division of multi-time-scale nested optimal scheduling model

The first level submodel takes a year as the scheduling period and a month as the scheduling scale. At the end of the year, an annual scheduling plan for the next year should be made for cascaded hydropower reservoirs. This submodel optimizes the annual scheduling for long-term benefits using monthly incoming runoff forecasts for the whole year. The second level submodel takes a month as the scheduling period and ten days as the scheduling scale. The initial and final levels of the second level model are determined by the calculated water level of the first level model. Because 6 days is the
forecasting period with better accuracy for short-term runoff forecasting, the third level submodel takes 6 days as the scheduling period and the day as the scheduling scale. The optimized scheduling initial and final water levels for the 6-day scheduling period are determined by the linear interpolation of the initial and final water levels for the second level. To make full use of the latest runoff forecast information, the model optimization scheduling calculations are updated on a rolling basis with a certain frequency. The model updates the annual residual period optimal scheduling calculation and the next month optimal scheduling calculation for every month. Daily, the model updates the optimal scheduling calculations for the next 6 days scheduling period.

2.2. Medium- and long-term optimal scheduling model
The medium- and long-term optimal scheduling model is used for the first annual scheduling period and the second monthly scheduling period. The model aims to maximize the power generation benefits of the cascaded hydropower reservoirs.

(1) Objective function
The Medium- and long-term optimal scheduling model for cascaded hydropower reservoirs takes the maximum power generation as the optimization objective.

\[
\text{max } E = \sum_{i=1}^{M} \sum_{t=1}^{T} N_{i,t} \Delta T_t = \sum_{i=1}^{M} \sum_{t=1}^{T} K_{i,t} Q_{i,t} H_{i,t} \Delta T_t
\]

Where \( E \) denotes the total power generation of cascaded hydropower reservoirs during the dispatching period, \( T \) is the number of periods during the dispatching period, \( M \) is the number of cascaded hydropower reservoirs, \( N_{i,t} \) denotes the power output of the \( i \)th hydropower reservoir in period \( t \), \( K_{i,t} \) is the corresponding power output coefficient, \( Q_{i,t} \) is the corresponding generation quoted flow, and \( \Delta T_t \) denotes the period length of period \( t \).

(2) Constraints
1) Water balance equation
\[
V_{i,t+1} = V_{i,t} + \left( I_{i,t} - Q_{i,t} - S_{i,t} \right) * \Delta T
\]
Where \( V_{i,t} \) is the reservoir capacity of the \( i \)th hydropower reservoir at the beginning of time period \( t \), \( I_{i,t} \) is the incoming flow, \( Q_{i,t} \) indicates the generation flow, and \( S_{i,t} \) indicates the disposal flow.

2) Water storage level constraints
\[
Z_{i,t} \leq Z_{i,t} \leq Z_{i,t}^\text{max}
\]
\[
\left| Z_{i,t} - Z_{i,t} \right| \leq \Delta Z_i
\]
Where \( Z_{i,t}^\text{min} \) and \( Z_{i,t}^\text{max} \) are the minimum and maximum water level limit for \( i \)th hydropower reservoir in time period \( t \), and \( \Delta Z_i \) indicates the maximum allowable water level change during the time period.

3) Output constraints
\[
N_{i,t}^\text{min} \leq N_{i,t} \leq N_{i,t}^\text{max} \left( H_{i,t} \right)
\]
Where \( N_{i,t}^\text{max} \) is the maximum output of \( i \)th hydropower reservoir in time period \( t \). The maximum output is determined by unit power characteristics, power transmission constraints, unit expected output, etc. \( N_{i,t}^\text{min} \) is the guaranteed output constraint.

4) Flow constraints
\[
Q_{i,t}^\text{min} \leq Q_{i,t} + S_{i,t} \leq Q_{i,t}^\text{max}
\]
Where \( Q_{i,t}^\text{max} \) is the maximum discharge flow of \( i \)th hydropower reservoir in time period \( t \), and \( Q_{i,t}^\text{min} \) is the minimum discharge flow. The maximum and minimum discharge flow is generally determined by the dam discharge capacity, the river ecology, water supply and other comprehensive water demand in different periods.

5) Boundary constraints
where \( Z_{i}^{\text{begin}} \) is the initial water level of the hydropower reservoir and \( Z_{i}^{\text{end}} \) is the final water level at the end of the dispatch period.

6) Water head calculation formula

\[
H_{i,j} = \left( Z_{i,j} + Z_{i,j+1} \right) / 2 - Z_{j}^{\text{ave}} - H_{i,j}^{\text{loss}}
\]

where \( H_{i,j}^{\text{loss}} \) indicates the head loss.

7) Output coefficient calculation formula

\[
K_{i,j} = K \left( H_{i,j}, Q_{i,j} \right)
\]

where the output coefficient \( K_{i,j} \) is a function of the head and the generation flow.

2.3. Short-term optimal scheduling model

Compared with the medium- and long-term model, the overall optimization objectives and constraints of the short-term model are basically the same. However, due to the distance between two hydropower reservoirs, the daily scale calculation cannot directly use the discharge flow and the interval flow as the boundary constraints of the same day. Therefore, the short-term optimization model considers the time lag of runoff propagation between the hydropower reservoirs. Both the medium- and long-term optimization model and the short-term optimization model are solved by the Successive Approximation Method of Dynamic Programming (DPSA) coupling the Progressive Optimal Algorithm (POA). Firstly, apply Dynamic Programming to calculate the optimal water level process line of a single reservoir separately. Secondly, fix the water level process line of the second reservoir to the \( N \)th reservoir, and use the POA algorithm to optimize the water level process line of the first reservoir. Thirdly, fix the water level process line of the first reservoir as well as the third reservoir to the \( N \)th reservoir, and apply the POA algorithm to optimize the water level process line of the second reservoir. With this traversal to optimize all reservoirs, the water level process line of all reservoirs is obtained. Finally, judge whether the value of this time meets the accuracy requirement compared with the result obtained from the previous calculation, if it does, stop the calculation and output the result, otherwise, go back to the first reservoir and continue the iterative calculation.

3. Results and Discussion

The developed model is applied to solve the optimal dispatching problem of four cascaded hydropower reservoirs (namely, Xiluodu, Xiangjiaba, Three Gorges, and Gezhouba) located at the Yangtze River. The model takes the actual data of cascaded reservoirs in 2018 as calculation boundary conditions. The results of the rolling update optimal dispatch calculation for the annual period, the results of the monthly dispatch period, and the results of the daily rolling update optimal dispatch calculation are obtained. Since the main task of the flood period of the reservoir is flood control, the optimized calculated water level is strictly controlled at the flood control level, but the actual operating water process level is higher than the flood control level, so the pre-flood operating process is selected for comparison. The calculation results and actual operation data before the flood in 2018 are derived according to different calculation methods as shown in Table 1.

| Table 1. The actual generation and the calculated total generation of different period models for cascaded reservoirs (unit: billion kWh) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|----------------|
|                 | Jan             | Feb             | Mar             | Apr             | May             | Jun\(^a\)       | Total           | Increase percentage\(^b\) |
| Actual operation| 12.944          | 10.386          | 11.22           | 11.324          | 17.653          | 11.079          | 74.606          | 1.31%           |
| Annual period   | 8.038           | 8.871           | 9.976           | 14.081          | 15.953          | 16.775          | 73.694          | 2.56%           |
| Monthly period  | 8.913           | 8.883           | 9.962           | 14.103          | 15.9            | 16.312          | 74.073          | 2.04%           |
| Daily period    | 9.98            | 9.376           | 9.9             | 14.417          | 16.842          | 15.069          | 75.584          | -               |
Since the start of the Three Gorges flood period on June 10, the generation of Three Gorges and Gezhoubaba only counts the first ten days in June.

Calculation formula:

\[
\frac{\text{Daily period generation} - \text{This method generation}}{\text{This method generation}} \times 100\%
\]

Compare the results of the daily rolling update optimal dispatch calculation with actual operation. As shown in table 1, the total generation of the cascaded reservoirs during the pre-flood period in 2018 calculated by the daily model is 75.584 billion kWh, and the actual generation of the whole cascaded reservoirs in the same period is 74.606 billion kWh. The results of the optimized calculation increase 1.31% compared with the actual generation. The result shows that the developed model can effectively increase the power generation benefit of cascaded hydropower reservoirs. Compare the operation process of the water level before the 2018 flood period. As shown in figure 2, compared with the actual operation, each reservoir keeps a high water level operation and lowers the water level right before the flood period. This operation process can keep a high head to increase the output as much as possible while lowering the level to the flood limit level before the flood to ensure safety.

Figure 2. Actual vs. daily scale optimized water level process of the cascaded reservoirs before 2018 flood period

Compare among the results of each optimal model with different period lengths. As shown in table 1, the results of the optimal dispatch for the monthly period are improved compared to the results of the optimal dispatch for the annual period and the results of the optimal dispatch for the daily period are improved compared to the results of the optimal dispatch for the monthly period. On the one hand, the forecasted runoff is dryer than the actual runoff, and the rolling update of the runoff forecast will make the calculation closer to the actual runoff. On the other hand, as shown in figure 3, the finer-scale optimization calculations on top of the upper-level optimization results can further expand the optimization search space.

4. Conclusions
The optimal scheduling of power generation for the cascaded hydropower reservoir based on deterministic incoming water cannot consider the risk of uncertainty. With the introduction of stochasticity, neither the explicit stochastic optimization with incoming water as a stochastic process nor the implicit stochastic optimization with a long series of optimization results analyzed by incoming
water history can make use of runoff forecasts, especially the short-term accurate runoff forecast information. At the same time, the above-mentioned optimal scheduling method with a fixed scheduling period cannot balance the benefits of long-term and short-term for the cascaded hydropower reservoirs. In this paper, a multi-time-scale nested optimal scheduling model for cascaded hydropower reservoirs is presented to solve the problem. And the model is applied to the optimal dispatching problem of four cascaded hydropower reservoirs (namely, Xiluodu, Xiangjiaba, Three Gorges, and Gezhouba) located at the Yangtze River. The results show that the developed model can better coordinate the medium- and long-term benefits with the short-term benefits, make full use of the latest forecast information, and improve the power generation of the cascaded reservoirs.

![Figure 3](image_url)

**Figure 3.** the water level process of each optimal model with different period lengths

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