Research on the Hydropower Generation Optimal Scheduling of Larger-Scale Cascade Hydropower Stations on Jinsha River and Lancang River

Dajun Si¹, Yuan Wang², Shuhao Liang², Yaowu Wu², Wangxi Zhang², Shiru Huang² and Bingran Wang²

¹Power Grid Planning and Construction Research Center Yunnan Power Grid Co., Ltd. Kunming, China
²State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan 430074, China

892507647@qq.com

Abstract. There are some characteristics, such as multi-dimensional, stochastic inflow, non-uniform service and scheduling subjects, in optimal scheduling of power generation. The problem is also subjected to hydrological and meteorological conditions, operation control, water demand, and loads of the power grid. Aiming at the electric power and energy balance problem in the high hydropower system, this paper uses the typical annual load curve to analyse the electricity power and energy balance, so as to better consider the influence of seasonal differences in hydrological conditions on the storage capacity of adjustable hydropower stations and the start-up of thermal power stations, and establish a mid-long term model of hydropower generation optimal scheduling of large-scale cascade hydropower stations. Taking the cascade hydropower stations in the Jinsha River and Lancang River as examples for simulation analysis, and using GUROBI to solve the model, the correctness and effectiveness of the proposed optimal scheduling model are verified.

1. Introduction

Hydropower is currently the clean energy with the highest development ratio, and the proportion of installed capacity in southwestern China is increasing [1]. Coordinating the optimized operation of cascade hydropower stations with thermal power, wind power and other power sources and give full play to the regulation capabilities of cascade hydropower, which is of great significance to the balance of power and electricity in high hydropower systems [2]. At present, there are abundant research results on the electricity power and energy balance in power system with high-proportion hydropower stations. Most of the existing studies are based on the balance of power and electricity on a typical day to optimize the day-ahead dispatch of cascade hydropower [3]. Most of the existing studies are based on the electricity power and energy balance on a typical day, and aim at the day-ahead optimal dispatch of cascade hydropower [4]. Based on the existing research, this paper uses the typical annual load curve to analyse the electricity power and energy balance, and proposes a mid-long term coordinated optimal scheduling model for cascade hydropower stations, which can better consider the influence of seasonal differences in hydrological conditions on the storage capacity of adjustable hydropower stations and the start-up of thermal power stations.
2. General situation of cascade hydropower development in Yunnan Province

As of the end of March 2020, the installed capacity of power generation in Yunnan Province was approximately 96,050MW, of which more than 70% of the installed capacity was hydropower [5]. From 2015 to 2020, a large number of hydropower projects in Yunnan were commissioned, and the installed capacity has increased by more than 20% [6]. Although Yunnan Province has planned a large number of high-energy-consuming projects to consume electricity, due to the impact of the new economic normal, the construction of high-energy-consuming projects lags behind, and the demand for electricity in the province has not increased. The intensive commissioning of hydropower installations and the sluggish demand for electricity have led to a sharp deterioration in the power supply and demand pattern in Yunnan Province. With the increase in power transmission year by year, the power transmission lines have basically been operating at full capacity during the high-water season, and the newly added hydropower cannot be effectively absorbed, resulting in serious water abandonment in Yunnan Province during the high-water season.

The hydropower resources of Yunnan Province are mainly concentrated in the Lancang River and Jinsha River basins. The installed capacity of the two basins accounted for 65% of the province's hydropower, and the power generation accounted for 63% of the province's hydropower. The water level and storage capacity of the hydropower stations in the Jinsha River and Lancang River basins are shown in Figure 1 respectively. The Lancang River in Yunnan Province adopts a “two-reservoir and six-level” development plan, with Xiaowan and Luozhadu as the core power stations, giving full play to the good regulation performance of cascade hydropower, coordinated and optimized dispatch of cascade hydropower, and realizing accumulation and replenishment, which can also improve the economic benefits of cascade hydropower. The Xiluodu Hydropower Station on the Jinsha River is currently the largest hydropower station built in China except for the Three Gorges Hydroelectric Power Station. Xiluodu Hydropower Station is one of the cores of cascade hydropower in the lower reaches of the Jinsha River.

Figure 1. Basic Situation of Cascade Hydropower on Lancang River and Jinsha River.
3. Mathematical model of the electricity power and energy balance of power system with high proportion of cascade hydropower

3.1. Objective function

The operation optimization model constructed in this paper aims at minimizing the overall operating cost of the power system, including the power generation cost of thermal power plants, the start and stop costs of thermal power plants, and the penalty cost of water abandonment of cascade hydropower. The objective function is as follows:

$$\min \sum_{i=1}^{n} \left[ \sum_{t=1}^{T} \left( F_i(P_i) + SU_{it} + SD_{it} \right) + \sum_{j=1}^{n_h} C_{Hij}^H \right]$$

$$F_i(P_i) = r_i \times \left( a_i P_i^2 + b_i P_i + c_i \right)$$

$$C_{Hij}^H = c_{Hij}^H \times \Delta Q_{ij}$$

In the above formula, $F_i(P_i)$ is the coal consumption cost function of thermal power station $i$, which is generally a quadratic function; $P_i$ is the output power of the thermal power plant $i$ at time $t$; $SU_{it}$ and $SD_{it}$ are the fuel consumption cost of the thermal power station $i$ at time $t$ when it is turned on and off; $C_{Hij}^H$ is the penalty cost of abandoning water of hydropower station $j$ at time $t$; $c_{Hij}^H$ is the abandonment penalty coefficient of hydropower station $j$; $\Delta Q_{ij}$ is the discarded water volume of hydropower station $j$ at time $t$; $r_i$ is the variable of start and stop of thermal power unit $j$ at time $t$, 1 means start, 0 means stop; $a_i, b_i, c_i$ is the coal consumption cost coefficient of thermal power unit $i$.

3.2. Operational constraints of hydropower stations

The power generation of a hydropower station is mainly determined by three factors: power generation efficiency $\eta_j$, water head $H_{jt}$ and power generation flow $Q_{jt}$ [7]. The transfer function of a hydropower station is as follows:

$$P_{jt} = g \eta_j Q_{jt} H_{jt}$$

In the formula, $P_{jt}$ is the power generation of the hydropower station $j$ at time $t$; $g$ is the acceleration of gravity, generally taken as 9.81; $\eta_j$ is the power generation efficiency of a hydropower station, for different hydropower stations, the power generation efficiency is related to the water head and flow rate, and is generally taken as a constant in the mid-long term electricity power and energy balance; $Q_{jt}$ is the power generation flow of the hydropower station $j$ at time $t$; $H_{jt}$ is the water head of the hydropower station $j$ in time $t$. The generated power $P_{jt}$ of the hydropower station is subject to the upper and lower power limits of the unit and the slope of the hydropower station, as shown below:

$$P_{jmin} \leq P_{jt} \leq P_{jmax}$$

$$\Delta_j \leq P_{jt} - P_{jt-1} \leq \Delta_j$$

In the formula, $P_{jmin}$ and $P_{jmax}$ are the minimum and maximum limits of the output of the hydropower station $j$; $\Delta_j$ is the maximum power climbing limit of the hydropower station $j$. 


3.2.1. Run-of-river hydropower station. Because the run-off-river hydropower station has no capacity to adjust the storage capacity, the power generation flow $Q_{jr}$ of the runoff hydropower station is related to the run-off value $R_{jr}$ of the hydropower station and the maximum power generation flow $Q_{jr}^{\text{max}}$. Let $f_{jr}$ be a variable from 0 to 1, which is used to indicate whether the run-off value $R_{jr}$ of the hydropower station exceeds the maximum power generation flow. If $f_{jr}$ is 1, it means that the run-off of the hydropower station exceeds the maximum power generation flow, and the runoff power station generates power. Conversely, if the run-off value of the hydropower station is less than the maximum power generation flow, all the run-off value of the hydropower station is used for power generation. The calculation formula is as follows:

$$-(1-f_{jr})M \leq R_{jr} - Q_{jr}^{\text{max}} \leq f_{jr}M$$ \hspace{1cm} (7)

$$-f_{jr}M + R_{jr} \leq Q_{jr} \leq R_{jr} + f_{jr}M$$ \hspace{1cm} (8)

$$-(1-f_{jr})M + Q_{jr}^{\text{max}} \leq Q_{jr} \leq Q_{jr}^{\text{max}} + (1-f_{jr})M$$ \hspace{1cm} (9)

$$\Delta Q_{jr} = R_{jr} - Q_{jr}$$ \hspace{1cm} (10)

3.2.2. Adjustable hydropower station. Adjustable hydropower stations have better regulation capabilities and can be flexibly tracked according to changes in system load. The power generation flow constraint and storage capacity inequality constraint of adjustable hydropower station $j$, the storage capacity balance constraint of adjustable hydropower station $j$, and the abandonment constraint formula of adjustable hydropower station are respectively as follows:

$$Q_{jr}^{\text{min}} \leq Q_{jr} \leq Q_{jr}^{\text{max}}$$ \hspace{1cm} (11)

$$V_{jr}^{\text{min}} \leq V_{jr} \leq V_{jr}^{\text{max}}$$ \hspace{1cm} (12)

$$V_{jr} = V_{jr-1} + R_{jr} - Q_{jr} + \Delta Q_{jr}$$ \hspace{1cm} (13)

$$\Delta Q_{jr} \geq 0$$ \hspace{1cm} (14)

In the formula, $V_{jr}$ is the storage capacity of the hydropower station $j$ at time $t$; $V_{jr}^{\text{min}}$ and $V_{jr}^{\text{max}}$ are the minimum and maximum storage capacity limits of the hydropower station $j$ respectively. Power generation head of the adjustable power station is determined by the upstream and downstream water levels, that is, the water head changes with the change of the storage capacity. The power generation head of the adjustable power station is a linear function of the reservoir capacity, as shown below:

$$H_{jr} = h_{0,j} + \alpha V_{jr}$$ \hspace{1cm} (15)

3.2.3. Cascade hydropower station. Cascade hydropower stations are a special kind of adjustable hydropower stations. The upstream and downstream adjustable hydropower stations are closely connected and have significant mutual influence. The current inflow of adjustable hydropower stations includes the natural inflow and the power generation flow of the upper-level hydropower station. In addition, there is a certain distance between upstream and downstream adjustable hydropower stations, that is, the time lag effect of water flow needs to be considered. Similar to ordinary adjustable hydropower stations, cascade hydropower stations must also meet generation flow constraints, storage capacity inequality constraints, start and end storage capacity constraints of adjustable hydropower
stations, and non-negative waste water volume constraints. However, the storage capacity balance constraints of cascade hydropower stations need to consider the generation flow and water flow time lag of the upper hydropower station.

\[ V_j = V_{j-1} + R_j + Q_{j-1,t} - Q_j + \Delta Q_j \]  

In the formula, \( \tau_j \) is the water flow time lag of hydropower station \( j \); \( Q_{j-1,t} \) is the power generation flow of the upper-level hydropower station \( j-1 \) at time \( t-\tau_j \).

3.3. Operational constraints of thermal power units

Thermal power plants need to meet the constraints of the maximum and minimum output capacity, the minimum start and stop time constraints of the unit, the consumption constraints of starting and shutting down the coal, as well as the upward and downward climbing constraints.

3.4. Power system operation constraints

System constraints require that the power system should meet load balance at every moment, as shown below, in the formula, \( L_t \) is the system load at time \( t \).

\[ \sum_{j} P_{j,L} + \sum_{i} P_{i,R} = L_t \]  

4. Linearization processing of hydropower output conversion function

When calculating the power output of adjustable hydropower stations in the electricity power and energy balance model, the head-storage capacity function (Equation (15)) needs to be substituted into the hydropower conversion function (Equation (4)) to obtain the relationship between the power generation of the hydropower station and the generation flow and storage capacity.

\[ P_j = g_j \eta_j Q_j \left( h_0, j + \alpha_j V_j \right) \]  

\( P_j \) in equation (18) is a quadratic function multiplied by the generation flow rate and the storage capacity, which makes the stochastic power and electricity balance model a nonlinear problem, which brings difficulties to the model solving. At this time, within the upper and lower limits of the reservoir capacity, the storage capacity is divided into several sections, and the average storage capacity of the section is used for calculation within the storage capacity range of each section [8]. The specific steps of linearization processing of hydropower output conversion function are as follows:

\[ \sum_{l=1}^{L} I_{j,l}^f = 1 \]  

\[ V_{j,0}^L = V_{j,L}^L \]  

\[ V_{j,0}^0 = V_{j,L}^0 \]  

\[ P_j = \lambda_j Q_j \left| V_{j,L}^0, V_{j,0}^L \right| = \sum_{l=1}^{L} I_{j,l}^f \lambda_j Q_j \]  

In the formula, \( I_{j,l}^f, ..., I_{j,L}^f \) represents hydropower station \( j \), which can be discretely divided into \( L \) segments, and the state variable of each segment takes the value 0 or 1; the reservoir capacity is discrete into \( L \) section, and the range of the first section is \( \left[ V_{j,0}^{L-1}, V_{j,0}^L \right] \).
5. Case studies
In order to verify the effectiveness of the mid-long term model of hydropower generation optimal scheduling of large-scale cascade hydropower stations proposed in this paper, Yunnan Province, which has a high proportion of hydropower generation, is used as an example for analysis. This article mainly analyses the operation optimization dispatching of the cascade hydropower stations on the Lancang River and the Jinsha River in Yunnan. At the same time, it also includes the optimization of the thermal power units in the provincial power system. The maximum load of the system is 34,340MW. There are 105 thermal power stations with a total installed capacity of 18,240MW. The total installed capacity of hydropower stations is 43,170MW. The total installed capacity of hydropower accounts for up to 70%. The hydropower stations include all the cascade hydropower stations built on the Lancang River and the Jinsha River in Yunnan, including 6 on the Lancang River and 7 in the Jinsha River. Using the method proposed in this paper to solve the above model, the monthly average coordinated output curves of thermal power, hydropower on the Lancang River, and hydropower on the Jinsha River are obtained as shown in Figure 2.

6. Conclusion
The mid-long term coordinated optimal scheduling model for cascade hydropower stations proposed in this paper can better consider the influence of seasonal differences in hydrological conditions on the storage capacity of adjustable hydropower stations and the start-up of thermal power stations, which can provide guidance for the operation of power systems with a high proportion of hydropower.

7. References
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Acknowledgments
This work was sponsored by China Southern Power Grid Science and Technology Project (0500002020030304GHJ00006).