Generation Scheduling of Hydro-dominated Provincial Power Grid: Problems and Solutions

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Abstract. Hydro-dominated power grids such as Sichuan and Yunnan in China face many new problems in power generation scheduling that have not been encountered in the small- and medium-sized hydropower systems. This brings great challenges to the safety and efficiency of power system operations and large-scale absorption of clean energy such as hydropower. Sichuan Power Grid whose hydropower capacity ranks first in the country is taken as the background. With its hydropower status and actual operation requirements, this study analyzes several main problems of hydro-dominated power system operations, including curse of dimensionality of large-scale hydropower plants, generation safety control of giant hydropower units, hydropower transmission and absorption in flood season, and coordinated operations of inter-provincial hydropower plants on main streams. With the theory of hydropower optimization and practical experiences, this study also puts forward appropriate suggestions and strategies.

1. Introduction

As is well-known, China is one of the countries with the most abundant hydropower resources in the world, whose total theoretical and technical exploitable capacity reach 694 million kW and 540 million kW, respectively. However, majority of the nation’s hydropower resources are distributed in the western region, especially in the southwest region. According to the literature about hydropower resources [1], the six provinces in Southwest China are endowed with 360 million kW of hydropower resources, accounting for 72% of the nation’s total [2-3]. The two provinces, Sichuan and Yunnan, rank first and second, with over 100 million kW, are China’s main hydropower base and the important transmission terminal of "Power Transmission from West to East ". For example, after 20 years of high-speed hydropower development, the installed hydropower capacity of Sichuan has achieved great development, reaching 78.4 million kW and accounting for 79.2% of the whole provincial power supply. This scale is the largest in all provincial power grids in China, and close to Canada (about 81 million kW), which ranks fourth in the world in hydropower [4].

However, due to the rapid growth of hydropower installed capacity, the lack of electricity demand in the hydro-dominated provinces, the lagging construction of power transmission channels and other comprehensive factors, as well as the rapid development of new energy, hydropower curtailment is becoming severe. Especially in the flood season, hydropower transmission is seriously hindered. The problem of hydropower curtailment of hydro-dominated provinces in Southwest China, led by Sichuan...
Province, is very prominent for the past few years [5]. In 2017 and 2019, therefore, the central government reports successively focused on solving it. In 2020, the State Council’s "guiding opinions on promoting the western development in the new era to form a new pattern" once again mentioned: “continue to increase the construction of key trans-provincial transmission channels such as the power transmission from West to East, and improve the transmission capacity of clean power; Strengthen the construction of peak load regulation capacity of power grid, and effectively solve the problem of abandoning wind, light and water". Therefore, how to effectively promote the absorption of large-scale hydropower in Sichuan and other hydro-dominated provinces and alleviate the serious power curtailment problem has become a major issue and real challenge for power system operations and management.

In Sichuan Power Grid, six hydropower transmission channels have been constructed in its main power network, including Sichuan–Chongqing lines in the East and several 500 kV high voltage (HV) transmission grids in the north and south. With the transfer of Southwest Power Grid to asynchronous interconnection operation, the transmission capacity of Sichuan Hydropower channels and important power sections is greatly reduced due to the stability constraints of large power grids. In addition, the Ya’an power transmission enhancement project, Kangshu series compensation project and Shujing third circuit line project have been put into operation in recent years. Sichuan’s water and power transmission capacity has been effectively released. After considering the subsequent Yazhong direct current(DC) project, Sichuan will provide a very favorable condition for reducing the hydropower curtailment. In this case, it is urgent to explore scientific, reasonable and efficient dispatching methods for large-scale hydropower system so as to promote the reasonable absorption of hydropower by an interconnected and wide power grid platform [6].

Therefore, this study analyzes the challenges faced by hydro-dominated power system operations. Four main problems are presented, including curse of dimensionality for optimizing large-scale hydropower plants, the safe operation of cascaded hydropower plants in the main stream, hydropower absorption, and inter-provincial dispatching operation. Taking Sichuan Power Grid as the background, preliminary suggestions and strategies are put forward in order to provide support for hydropower system operations.

2. Main Operation Problems for Hydro-Dominated Hydropower Systems

2.1. Curse of Dimensionality for Optimizing Large-Scale Hydropower Plants

As mentioned above, Sichuan Power Grid has the largest installed capacity of hydropower in China and even in the world. In this province, cascaded hydropower systems are also quite large. On the lower reaches of Yalong River, Dadu River and Jinsha River, there are more than 10 million kW. Among them, Yalong River is planned to construct 23 reservoirs and hydropower plants with an installed capacity of 28.85 million kW; Dadu River is projected with 22 reservoirs and plants with an installed capacity of 23.4 million kW. There are huge hydropower plants on the lower main stream of Jinsha River, whose installed capacity exceeds more than 42 million kW, of which Wudongde, Xiluodu and Xiangjiaba have been put into operation. Theoretically speaking, these large-scale river basin cascades have entered the disaster barrier of hydropower optimization dimension recognized at home and abroad [7-8], and need new theoretical methods and technical support.

The hydropower interconnection of cascaded hydropower plants in the main streams of Yalong River, Jinsha River and Dadu River requires long-distance hydropower transmission across river basins, provinces and regions. Under the complex power network structure, the shortage of hydropower transmission channels, the weakness of grid capacity in remote areas within the network and the blockage of hydropower channel in flood season need more attention. Specifically, considering the complex time-space coupling contract of hydraulic and electric power, breaking through the transmission limitation of power network and market competition, coordinating the load difference, power supply difference, hydrological difference, interest between power exporter and
recipient, etc., are major tasks. These are quite important to improve the capacity of hydropower integration and relieve hydropower curtailment in flood season.

The optimal operations of the above-mentioned provincial and cascaded hydropower systems suffer from a great challenge in reasonably modeling such a large system and efficiently solve it. Such a large-scale and complex optimization problem is extremely challenging, requiring a new perspective to develop scientific and efficient modeling and solution methods.

2.2. Day-Ahead Generation Scheduling with Head-Sensitive Restricted and Forbidden Zones
Most of giant hydropower plants located in Sichuan province are designed with high water head, such as Xiluodu, Xiangjiaba, Jinping, Pubugou, etc. Such kind of hydropower plants is usually installed with large turbine units which have head-sensitive restricted and forbidden zones. The characteristics limit the range and amplitude of power generation. When giant hydropower plants respond to peak loads of multiple power grids, the power generation often needs to change greatly, which leads to a large variation of the water head and turbine discharge. In this case, generating units will frequently cross the forbidden zones or operating in the restricted zones for a long time. The complexity of short-term and real-time operation control is thus aggravated. How to avoid the complex and irregular operation zones reasonably and quickly and to ensure the safety and reliability of power grids and power plants is a major technical problem. This is also a common challenge for cascaded hydropower plants on the main streams of the southwest rivers, requiring scientific and effective methods and strategies.

2.3. Hydropower Integration and Transmission in Flood Season
From the perspective of inflow, the annual runoff distribution of southwest rivers usually has obvious seasonal characteristics. For example, about 80% of inflow of Jinsha River, Yalong River, Lancang River and Dadu River is distributed in the flood season (from May to October), especially in the main flood season (from June to August). These inflow characteristics lead to huge pressure of reservoir storage and power transmission. From the perspective of the transmission channel, this country has continuously promoted the construction of UHV transmission channel in recent years. However, the transmission capacity is still lower than the power source development at this stage. In addition, the integration of wind and solar energy and other new energy resources is rapidly increasing, occupying the transmission channel and thus making hydropower transmission and absorption still face great pressure. Sichuan Power Grid is one of the largest and most complex provincial power grids in the State Grid system. The 500kV power network covers all cities in the whole province. The load center forms a ladder shaped double loop network. Outside the province, it is interconnected with the power grids of East China, Central China, Northwest China, Tibet and Chongqing through 8 ultra-high voltage AC and 4 ultra-high voltage DC lines. The power from the lower reaches of Jinsha River and Yalong River is transmitted to East China. Currently, the inter-provincial power transmission capacity has reached about 30 million kW. The complex structure of inter-provincial transmission network especially the hybrid of AC and DC increases the complexity of hydropower operations and transmission. This makes hydropower system dispatching face a series of new problems, such as the formulation of DC lines, the coordination of multiple lines, and the safety of power transmission schedules and power allocation among multiple recipients.

2.4. Optimal Operations of Interprovincial Hydropower System
Xiluodu and Xiangjiaba hydropower plants on the main stream of Jinsha River are important backbone power sources for "Power Transmission from West to East", with an installed capacity of 12.6 million kW and 7.75 million kW, respectively, ranking the third and fifth in China. Xiluodu is the first hydropower plant with "one reservoir and two dispatching apartments" in China. Nine turbine units are installed on the left and right banks respectively, which need to deliver power to East China Grid and China Southern Power Grid, respectively. Xiangjiaba provide power through Fufeng UHVDC and Jinping cascaded hydropower plants provide power through Jinsu UHVDC for East China. Liyuan,
Ahai, Jin’anqiao, Longkaikou, Ludila and Guanyinyan in the middle reaches of Jinsha River are dispatched by Yunnan Power Grid and offer power for Yunnan, Guangdong, Guangxi and other provinces. Other cascaded hydropower plants on the main stream of Yalong River are connected into the Sichuan main network to meet the power demand of Sichuan and outer provinces. There are great differences in the scale, connection mode, load demand and dispatching relationship of trans-regional power transmission of cascaded and giant hydropower plants, which is essentially a large-scale inter-basin, inter-provincial and inter-regional coordination optimization problem. The scale and complexity of the problem are different from those of small- and medium- sized cascaded hydropower plants. For this problem, the spatial-temporal coupling of objectives and constraints is stronger, and the modeling and optimization solution are more difficult. This needs innovative theory and technology for the hydropower system operations.

3. Suggested Solutions for Hydro-Dominated Hydropower System Operations

3.1. Develop Practical Strategy for Dispatching Large-Scale Hydropower Plants

Similar to the large-scale hydropower system in Sichuan Power Grid, the number of hydropower plants usually reaches tens or more than 100, which are distributed in multiple different river basins. The plant composition, installed capacity, regulation ability, inflow and other characteristics of cascaded hydropower plants in different basins are different. Moreover, different power plants can be coordinated and regulated by multi-level dispatching agents, such as regional, provincial, and local dispatching centers. It is very difficult to directly solve such a large-scale and complex hydropower system by using classical dynamic programming or mathematical programming methods and technologies to describe connected grid structure and differential transmission requirements. It is necessary to design an efficient and practical strategy based on the engineering characteristics of the hydropower system.

There are three ways to solve the problem.

First, from the analysis of demand and engineering conditions, determine the hydropower plants that do not need to participate in the optimization, so as to reduce the plant number. For example, if the differences between the conditions of inflow, electricity control, load and other conditions are small compared with those last day, the previous generation schedules can be directly used as an initial recommended scheme for this kind of power plants. Thus, they only need to carry out simple hydraulic check to meet the conditions of water level and spillage control. As another example, when the whole installed capacity of some small- and medium- sized cascaded hydropower plants are small, their power generation scheme usually has little impact on the power grid. Such power plants can be self-regulated by the river’s dispatching center. In this way, the provincial power grid can directly use the obtained dispatching results.

Secondly, according to the geographical location and grid structure, all hydropower plants are grouped reasonably to reduce the number of optimized power plants in a single calculation. First, according to the basin where hydropower plants are located, they are divided into several groups without hydraulic connection. Second, the power plants at different grid connection positions are further divided into different small-scale groups. Third, considering the upstream and downstream sequence, the hydraulic balance relationship between adjacent upstream and downstream hydropower plants of different groups is established to meet the next step requirements of iterative optimization calculation.

Thirdly, the iterative optimization strategy of each group of power plants is designed according to the order from large to small. A suitable iterative optimization framework needs to be established. For any a group of power plants, when the scale is small, the classical methods such as step-by-step optimization, dynamic programming successive approximation or discrete differential dynamic programming can be used to solve the problem. When the scale is large, a variety of classical methods can be reconstructed to develop a multi-dimensional search algorithm to speed up the optimization
solution efficiency. For two groups of power plants without hydraulic connection, parallel computing can be introduced by using multi-core computer resources to further improve the calculation speed.

Based on the above strategies, a practical solution framework for large-scale hydropower system operations in hydro-dominated power grids can be constructed, which can meet the requirements of accuracy and timeliness of actual engineering.

3.2. Develop Short-Term Operation Strategy with Head-Sensitive Forbidden Zones
The power generation dispatching of giant hydropower plant, especially the short-term and real-time operation control, is directly related to the safety of power system. It is necessary to fully consider the irregular restricted operation zones and forbidden zones. The dynamic operation zones, the hydraulic connection of upstream and downstream hydropower plants are required to be considered to reasonably arrange the generating operation plan and real-time load regulation response. To solve this problem, we can design appropriate strategies from the actual engineering requirements.

In the preparation of day-ahead short-term schedules, it is usually necessary to determine the quarter-hourly power generation schedules for the next day or the next few days, where the power plant or unit is taken as the object. When the power plant is taken as the object, the boundary conditions of the restricted and forbidden zones of the unit should be converted into the corresponding area of the power plant in advance. This can avoid frequent unit commitment and load distribution in short-term optimal dispatching. Moreover, it is helpful to improve the optimization efficiency. When taking the unit as the object, it is necessary to combine the daily power generation of the power plant. In order to reasonably determine the safe and feasible region of each unit, the water head of hydropower plant is estimated.

In real-time operations, the start-up and shut-down of units and load adjustment scheme in the next few hours are determined on the base of the day-ahead generation schedules. Here, the demand changes of load and inflow are considered. In this case, the power generation schedules usually do not change greatly. Therefore, the adjusting method can be adopted to deal with the constraint of restricted and forbidden zones. First of all, it is necessary to judge the change process of reservoir level and water head by hydraulic calculation. In this way, the restricted operation area of different units can be identified dynamically, and then a comparative analysis and dynamic adjustment can be made according to the output of each unit.

On the other hand, considering the timeliness requirements of short-term and real-time operation control, the relationship between water level/head, generation and forbidden zones can be extracted from the actual operation data samples. Thus, the safe and efficient unit operation interval can be identified in advance to arrange reasonable generation schedules quickly.

3.3. Develop Short-Term Coordination Strategy for Multiple Power Transmission Lines
As mentioned above, Sichuan Power Grid is interconnected with East China, central China, Northwest China, Tibet, Chongqing and other power grids through 8 UHVAC and 4 UHVDC lines, which are the main channels for its power transmission. Due to obvious differences in transmission capacity and operation mode of different transmission lines, as well as the grid connection mode of hydropower plants and the load demand of receiving power grids, it is very important to make full use of these differences to carry out complementary coordination among transmission lines. This will help to make full use of channel transmission capacity and enhance the scale of hydropower transmission. It is also beneficial to promote hydropower absorption and reduce the hydropower curtailment in flood season.

This section and the next section will propose complementary coordination strategies of multiple transmission lines from long-term and short-term scales, respectively.

In the short-term operations, the daily energy transmitted by each channel is usually given. Therefore, we can take advantage of the difference of load characteristics among receiving power grids and capacity differences among transmission lines to optimize and coordinate the power transmission profiles of each line. The purpose is to improve the quality of transmission power.
schedules, promote the hydropower absorption during off-peak hours, and enhance the load response to the receiving power grids.

For the coordination problem involving multiple lines and multiple receiving power grids, the following steps can be used to determine the transmission power schedules of each line.

Step 1: determine the daily transmission energy of each line and the load demand of the receiving power grid; set the power fluctuation rate at adjacent periods for each line as $\Delta R_i$; set the duration time as $v_i$.

Step 2: define the number of iterations as $n$; set the transmission energy of a line in the $n$th iteration as $E_{i,n}^t$.

Step 3: find the lowest load point and denote it as $w$; Assume that there are $u$ combinations of continuous load points including point $w$, increase the load of these combination points by $\Delta R_i$, respectively; optimize the combination point with the minimum variance and increase the power of the line at this combination point; handle the maximum and minimum constraints, as well as climbing generation;

Step 4: judge whether the given daily power transmission is true. If so, set $l = l + 1$ and repeat Steps 1-4 until all lines meet the predetermined power target; if not, set $n = n + 1$ and repeat Steps 3 and 4.

3.4. Develop Long-Term Coordinated Strategy for Multiple Power Transmission Lines

In the long-term operation, it is necessary to focus on the water level control strategy and power generation capacity of cascaded hydropower plants in each major river. Using the differences in inflow, regulation performance and transmission capacity among lines, the transmission power scale can be reasonably arranged. Thus, we can avoid the situation that some lines are idle or are insufficient. The following steps will be adopted to determine the long-term power complementary coordination strategy among different lines.

(1) The water level control objectives of major reservoirs are determined and the capability of hydropower system is estimated. Combined with the requirements of power grid operation and safety control, the final control water level target of each reservoir is determined, and the generation capability of hydropower system is reasonably estimated by considering inflow prediction.

(2) Considering the power generation capacity of each line, the transmission capability of the line, and the space of the receiving power grid, the external transmission scale of each line and the potential hydropower curtailment are analyzed.

(3) Carry out complementary coordination to improve the scale of power transmission. There are two main situations. The first is that multiple transmission lines are connected to the same receiving power grid. The second is that multiple hydropower plants transmit power through a same line. In the first case, the total capacity of the receiving power grid is taken as the control condition, and the transmission limit of each line is taken as the constraint. Thus, an optimization model of multiple lines is established. The target is to minimize the amount of spillage. The formulation is as follows:

$$\min F_i = \sum_{m \in \Omega} E_{m,t}$$

s.t. 

$$E_{i,t} \leq E_{i,t}^{\max}$$

$$E_{r,t} \geq \sum_{i=1}^{\Omega} E_{i,t}$$

where $E_{m,t}$ is the spillage of power plant $m$ in time period $t$; $\Omega$ is the set of hydropower plants associated with the external transmission line; $E_{i,t}$ is the external power transmission capacity of line $l$ in time period $t$; $E_{r,t}$ is the maximum outward transmission capacity of line $l$ in time period $t$; $E_{r,t}^{\max}$ is the maximum outward transmission capacity of line $l$ in time period $t$. The following steps can be used to determine the transmission power schedules of each line.
is the acceptance capability of receiving power grid in time period $t$; $\Omega_i$ is the set of transmission lines.

In the second case, considering the control targets of inflow and reservoir water level, the optimal operation model of hydropower plants with the power section constraint is proposed. The improved dynamic programming methods are used to optimize the operation schemes and generation schedules of each hydropower plants. The differences of hydrological compensation and regulation performance among power plants can reduce the loss of unnecessary spillage.

3.5. Optimize Power Transmission Schedules of Large-Scale Hydropower Plants

In the optimization of power transmission, it is necessary to consider the control strategy of giant hydropower plants in main rivers, as well as the transmission capacity, blocked hydropower capacity, power transmission framework agreement and other factors. Thus, we can analyze and determine reasonable transmission capacity which is taken as the control condition. The multi grid coordination optimization model is further considered to analyze the load peak change of the receiving power grids. The generation and transmission schedules of giant hydropower plants to meet the demand of power grid are determined through the coordination and optimization of mutual assistance among power grids.

Taking the water level as control objectives of the reservoirs and the power transmission framework agreement as the dispatching constraints, the optimal daily power transmission optimization model can be constructed by controlling the water level at the end of the horizon and the total transmission energy. The predicted inflow, the load of the power grid at the sending and receiving ends, and the limitation of the power network sections are need to be considered. On this basis, if the hydro-dominated power grid is faced with a large pressure of spillage, the control constraints of power transmission can be further relaxed, and the scheme of minimizing spillage is analyzed.

The optimization objective can be the maximum peak-shaving objective, which needs to consider the water level control constraints of reservoirs and power transmission constraints

$$Z_{m,T} = Z_{m}^n$$  \hspace{1cm} (2)

where $Z_{m}^n$ is the medium- and long-term water level control target of a reservoir. The control condition of power transmission is as follows:

$$E_{g,t} = \sum_{r=1}^{T} E_{g,t}$$  \hspace{1cm} (3)

where $E_{g,t}$ is the total electricity requirement of the operation horizon, which is determined by the multi-party framework agreement; $E_{g,t}$ is the external power transmission to the $g$ grid in period $t$. Combined with this constraint, the optimization model of daily power transmission needs to further consider the following constraints, that is, the amount of electricity distributed by the hydropower system to the external power grids and the provincial power grids in any period should be equal to the total power generation of the system.

$$E_{g,t} = \sum_{g=1}^{G} E_{g,t}$$  \hspace{1cm} (4)

In the actual operations, it is necessary to revise the overall power transmission conditions according to the actual requirements, and optimize and update the reasonable daily transmission power schedules day by day.

In particular, in the wet season, the hydro-dominated power grid is faced with a large pressure of spillage. At this time, we should make full use of the external transmission lines to reasonably increase the transmission power and reduce the pressure of the power grid. Therefore, the above constraints can
be relaxed, and the maximum hydropower absorption model can be used to determine the daily power transmission scheme by considering the acceptable capacity of receiving power grids.

4. Conclusion

In hydro-dominated power grids of southwestern China, the total installed capacity of hydropower is about to exceed 100 million kW, reaching about one fourth of the total installed hydropower capacity in China. How to dispatch and manage such a large-scale hydropower system is an important and challenging theoretical and practical issue that has never been seen in the hydropower history in the world. Based on the practical characteristics of hydropower system in Sichuan Power Grid, this study analyzes the major challenges of power generation dispatching in hydro-dominated power grid from four aspects, i.e., optimization dimension disaster of large-scale hydropower plants, operation safety of giant hydropower units, hydropower curtailment and inter-provincial hydropower system operations. According to the effective and practical principles, the system simplification, coordination of DC lines, coordination between power exporters and recipient are discussed. This paper puts forward appropriate suggestions and strategies from many aspects, such as power dispatching, which provides important reference for the safety, efficiency and economy of hydro-dominated power system operations.

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