Research on clearance model for electricity market with cascade hydropower stations

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Abstract—Together with power structural reform, the intended contribution target of carbon neutral and carbon peaking aims to promote the market-based consumption of renewable energy, which has become an essential task for the construction of China's power market. Cascade hydropower is a special form of hydro-generation, the upstream and downstream power stations have a close hydraulic coupling relationship with each other. In order to ensure the fair participation of all generation entities in the market and improve the feasibility of the transaction results, the operational characteristics of the cascade hydropower should be integrated into the market clearance model. In this paper, a day-ahead market case including six generation entities is designed, and the rationality and practicality of the clearance model are verified by analyzing the results of market transaction in different operation scenarios.

1. Introduction

Hydropower is a form of renewable energy with zero pollution and low operating cost, and it is often used due to the power peak regulation, thus improving the resources utilization efficiency and benefit to the whole society. Therefore, it occupies a significant position in the country's energy structure. By the end of 2020, China's full-caliber installed generation reached 2201GW and hydropower (including pumped storage) capacity reaching 370GW (17%), both of them ranking first in the world. With the strategic goals of energy transition, carbon peaking by 2030 and carbon neutrality by 2060 in China and power structural reform [1] [2], the participation of hydropower in the power market is to be expected [3].

According to foreign experience, hydropower directly participates in the power market as ordinary units in Northern Europe, the United Kingdom, Ontario (Canada), the PJM region (the United States), California (the United States) and New Zealand, which means it must submit bids for electricity transaction. Sichuan, as one of the first eight pilot provinces to launch the power spot market, adopts the design of the electricity spot market model that divides the abundant and dry periods. It means that hydropower participates in the market by bidding during the abundant period, and thermal power only stays in the minimum generation mode. Conversely, thermal power participates in the market by bidding during the dry period, and hydro-generation is adjusted according to the incoming water so that the proper consumption of hydropower can be guaranteed.
The water resources are rich in China’s southwest region and there are many cascade hydropower stations. The incoming water for the downstream power stations is related to the operation mode of upstream power stations, and the whole generation is arranged in the planning system according to the principle of energy-saving dispatching. In the power market environment, it is quite difficult to achieve joint operation of cascade hydropower by establishing an agency mechanism or a benefit sharing and compensation mechanism because the investment entities of China’s cascade hydropower are usually different [4][5]. When cascade hydropower stations participate in the market independently, market clearance without considering relevant constraints may lead to an imbalance between the cleared generation and the actual generation, making it difficult to execute the cleared results and causing market instability and water waste.

For the above problems, some scholars propose that upstream stations can participate freely in the market and downstream stations act as recipients of the electricity’s quantity and price [6], but this may negatively affect the fairness of the market and the participation rate of market entities. This paper aims to integrate the operation constraints into the clearance model from the top-level design of the power market, based on the hydraulic coupling relationship and output characteristics of the cascade hydropower stations, achieving the joint clearance of upstream and downstream stations and ensuring that the clearance results match the actual generation capacity.

2. The Day-ahead Market Clearance Model

2.1 The Day-ahead market optimization goal

The market clearance is based on the optimization objective of maximizing social welfare [7][8], which is equal to the difference between the cost that the electricity purchasers are willing to pay and the revenue that the generators expect to obtain. The construction of provincial electricity spot markets in China usually starts with a unilateral market model, which means users only declare their load demand (electricity quantity). Therefore, the market clearance objective can be simplified as minimizing the cost of generation. When hydropower and thermal power bid together using the time-phased bidding mechanism, the objective function of the market clearance model can be written as

$$\min \left( \sum_{t} \sum_{n} \sum_{k} \lambda_{n,k,t}^{t} \cdot P_{n,k,t}^{t} + \sum_{t} \sum_{n} C_{n,t} + \sum_{t} \sum_{m} \sum_{k} \lambda_{m,k,t} \cdot P_{m,k,t}^{y} \right)$$  \hspace{1cm} (1)

Where \( t, n, m \) and \( k \) represent the time period, thermal power plant, hydropower station and bidding capacity scope, respectively; \( \lambda_{n,k,t}^{t} \) and \( P_{n,k,t}^{t} \) are the bidding price and bid-winning quantity of thermal power plant \( n \) in capacity scope \( k \) in time period \( t \), and \( C_{n,t} \) is the start-up cost of thermal power plant \( n \) in time period \( t \); \( \lambda_{m,k,t} \) and \( P_{m,k,t}^{y} \) are the bidding price and bid-winning quantity of hydropower station \( n \) in capacity scope \( k \) in time period \( t \), respectively.

2.2 Constraints of the conventional clearance model

When the hydraulic coupling relationship and generation output characteristics of cascade hydropower are ignored, the conventional constraints of the day-ahead market clearance model mainly include system constraints, network constraints and plant constraints [9].

(1) Load balance constraints

For any time period, the sum of the bid-winning generation should be equal to the declared load demand:

$$\sum_{n} \sum_{k} P_{n,k,t}^{t} + \sum_{m} \sum_{k} P_{m,k,t}^{y} = \sum_{j} D_{j,t}, \forall t$$  \hspace{1cm} (2)

Where \( D_{j,t} \) is the load of user \( j \) in time period \( t \).
(2) Line flow constraints

\[-p_l^{max} \leq \sum_n \sum_k G_{l,n} p_{n,t,k}^t + \sum_m \sum_k G_{l,m} y_{m,t,k} - \sum_j G_{l,j} d_{j,t} \leq p_l^{max}, \forall t \tag{3}\]

Where \(p_l^{max}\) is the power flow transmission limit of line \(l\); \(G_{l,n}\), \(G_{l,m}\) and \(G_{l,j}\) are the power transfer distribution factors of thermal power plant \(n\), hydropower station \(m\), and user \(j\) to line \(l\), respectively.

(3) Upper and lower generation limits of plants

\[b_{n,t} p_{n,t}^{min} \leq P_{n,t} \leq b_{n,t} p_{n,t}^{max}, \forall t \tag{4}\]

Where \(P_{n,t}^{min}\) and \(P_{n,t}^{max}\) are the minimum and maximum technical output of thermal power plant \(n\), respectively; \(b_{n,t}\) is the 0-or-1 variable that represents the start-or-stop status of the thermal power plant \(n\) during the time period \(t\); \(b_{n,t} = 1\) represents the power-on status, and \(b_{n,t}=0\) represents the shut-down status.

For hydropower, there is no need to consider the start-or-stop status of stations, therefore the generation constraint is shown as follows:

\[0 \leq P_{m,t} \leq P_{m,t}^{max}, \forall t \tag{5}\]

Where \(P_{m,t}^{max}\) is the maximum technical output of hydropower station \(m\).

(4) Plant ramping constraints

\[P_{n,t} - P_{n,t-1} \leq \Delta P_n^r \cdot b_{n,t-1} + p_{n,t}^{min} (b_{n,t} - b_{n,t-1}) + p_{n,t}^{max} (1 - b_{n,t}), \forall t \tag{6}\]

\[P_{n,t-1} - P_{n,t} \leq \Delta P_n^d \cdot b_{n,t} - p_{n,t}^{min} (b_{n,t} - b_{n,t-1}) + p_{n,t}^{max} (1 - b_{n,t-1}), \forall t \tag{7}\]

Where \(\Delta P_n^r\) and \(\Delta P_n^d\) are the maximum ramp-up rate and the maximum ramp-down rate of thermal power plant \(n\), respectively. Hydropower stations usually perform better in output regulation and there is no need to consider ramping constraints.

In addition, the conventional day-ahead market clearance constraints include system positive and negative backup capacity constraints, system rotating backup capacity constraints, thermal power plants’ minimum continuous start-stop time constraints and thermal power plants’ maximum start-stop frequency constraints, which will not be repeated in this paper.

3. Constraints based on the operational characteristics of cascade hydropower stations

3.1 Hydraulic coupling relationship of cascade hydropower stations

For the most upstream hydropower stations, the inflow only depends on the interval incoming flow. The inflow of the downstream hydropower stations is determined by both the natural incoming flow of the interval and the drain flow of the upstream hydropower stations.

\[Q_{i,t}^{in} = I_{i,t} + \gamma Q_{up,i,t-\tau}^{out} \tag{8}\]

Where \(Q_{i,t}^{in}\) represents the inflow of hydropower plant \(i\) in time period \(t\); \(I_{i,t}\) represents the natural incoming flow of the interval; \(Q_{up,i,t-\tau}^{out}\) is the drain flow of the upstream hydropower plant in time period \(t - \tau\); \(\gamma\) is the channel attenuation coefficient and \(\tau\) is the time lag of the flow, which are both related to the layout of cascade hydropower stations.

Considering the presence of wasted water, the generation flow of the hydropower station is equal to the drain flow minus the wasted water flow, and the drain flow is equal to the inflow minus the storage flow.

\[Q_{i,t}^g = Q_{i,t}^{out} - Q_{i,t}^w = Q_{i,t}^{in} - Q_{i,t}^s - Q_{i,t}^w \tag{9}\]
Where \( Q_{it}^G, Q_{it}^{in}, Q_{it}^S, Q_{it}^{lw} \) and \( Q_{it}^{out} \) respectively indicate the generation flow, inflow, storage flow, wasted flow and drain flow of hydropower station \( i \) during time period \( t \). In the river’s dry period, if the reservoir has a huge regulation capacity, the wasted water can be ignored.

### 3.2 Power output characteristics of hydropower stations

The power output of the hydropower station is related to the generation flow and net water head. The net water head is a function of the real-time water level and tail water level for the reservoir, and the tail water level is a function of the drain flow. When the reservoir capacity is large, the change of net water head can be ignored during the day, and the non-linear relationship between the power output of the hydropower station and generation flow can be described as segmented linear function. During the operation day, the change range of the hydropower station’s generation flow is not large, and the relationship between the power output and generation flow can be further written as a linear function:

\[
P_{it} = \alpha Q_{it}^G + \beta
\]

Where \( P_{it} \) and \( Q_{it}^G \) are the power output and generation flow of hydropower station \( i \) in time period \( t \); \( \alpha \) and \( \beta \) are the segmented linear fitting parameters, which are determined by the operating agency according to the current reservoir water level forecast.

### 3.3 Hydropower station water level control constraints

During the operation day, the reservoir water level will change due to the hydropower station’s storage water. The storage volume \( \Delta Q_{it}^S \) is equal to the time integral of the storage flow, and since the day-ahead market clearance period \( \Delta t \) is only 15 minutes, therefore the product of the storage flow \( Q_{it}^S \) and the time interval \( \Delta t \) can be approximated as the storage volume \( \Delta Q_{it}^S \).

\[
\Delta Q_{it}^S = Q_{it}^S \cdot \Delta t
\]

When the storage capacity of the hydropower station is large enough, the water level change \( \Delta H_{it} \) caused by the storage of the reservoir during the day is small, and the reservoir area \( S_i \) can be considered as a constant value\([10]\).

\[
\Delta H_{it} \times S_i = \Delta Q_{it}^S
\]

The water affairs department have to consider the requirements of flood prevention, hydro-generation and coordination of different levels, therefore it will release the water level control constraints in each time period.

\[
H_{it}^{min} \leq H_{i,0} \sum_t \Delta H_{it} \leq H_{it}^{max}, \forall t
\]

Where \( H_{i,0} \) is the initial water level of hydropower station \( i \); \( H_{it}^{min} \) and \( H_{it}^{max} \) are the upper and lower water level limits of hydropower station \( i \) during time period \( t \), respectively.

### 3.4 Hydropower vibration zone constraints

The vibration zone refers to the power output range that the generation unit of the hydropower station needs to ensure safe operation.
Fig. 1 The schematic diagram of hydropower vibration zone

\[ P_{i,t} = \sum_{n=1}^{M+1} \delta_{i,n,t} P_{i,n-1}^u + \sum_{n=1}^{M+1} P_{i,n,t} \]  
(14)

\[ \sum_{n=1}^{M+1} \delta_{i,n,t} \leq 1 \]  
(15)

\[ P_{i,0}^u = P_{i,\text{min}}, \quad P_{i,M+1}^d = P_{i,\text{max}} \]

Where \( P_{i,n}^d \) and \( P_{i,n}^u \) are the lower and upper power output limits of vibration zone \( n \) for hydropower station \( i \); \( \delta_{i,n,t} \) is the 0-or-1 variable indicating whether the power output of the hydropower station \( i \) is in the feasible interval \([P_{i,n-1}^u, P_{i,n}^d]\) or not in time period \( t \). There are \( M \) vibration zones and \( M+1 \) feasible intervals. \( P_{i,n,t} \) is the magnitude of the power output when the hydropower station \( i \) operates in feasible interval \( n \) in time period \( t \).

\[ 0 \leq P_{i,n,t} \leq (P_{i,n}^d - P_{i,n-1}^u) \delta_{i,n,t}, \forall n = 1, 2, ..., M + 1 \]  
(16)

According to the above inequality constraints, the hydropower output can be limited into a certain feasible range.

4. Case study

4.1 Essential data

Based on the IEEE14-node system [11], this paper carries out a day-ahead market simulation. In the power generation side, the case study includes 6 market participants, where participant 1 to 4 are thermal generators, participants 4 and 5 are Cascade hydropower station located on the upper and lower reaches of a river basin respectively. The water flow delay between the two hydropower stations is set as an hour and the river basin attenuation coefficient is set as 1 (\( \gamma = 1 \)). In the user side, only bus load prediction is carried out.

In order to reduce the difficulty of solving process, it is assumed that each power generators can only summit a quantity-price curve which only includes one capacity segment, and the start-up cost of thermal power units is not considered. Additionally, constraints related to hydropower do not comprise consist of the constraint of hydropower vibration zone, and general constraints do not consider the constraint of
transmission capacity, positive and negative reserve capacity of the system, system rotation reserve capacity, minimum continuous start and stop time of thermal power unit as well as maximum start and stop times.

The case study is focus on the analysis of the influence of load fluctuation, water inflow and bidding strategy on bidding result of each market participants.

4.2 Basic scenario

The output upper and lower limits, ramping rate and quotation of each generator are set according to the table below.

| Generator          | Output upper limit (MW) | Output lower limit (MW) | Maximum upper/lower ramping rate (MW/h) | Quote (¥/MWh) |
|--------------------|-------------------------|-------------------------|-----------------------------------------|---------------|
| Thermal power 1    | 300                     | 100                     | 100                                     | 400           |
| Thermal power 2    | 650                     | 200                     | 250                                     | 450           |
| Thermal power 3    | 350                     | 120                     | 120                                     | 500           |
| Thermal power 4    | 420                     | 170                     | 150                                     | 600           |
| Hydropower 1       | 500                     | 0                       | 500                                     | 300           |
| Hydropower 2       | 400                     | 0                       | 400                                     | 250           |

Initially, four thermal power unit have been started up and is running at the minimum technical output state. Generation characteristic parameter, water level control and reservoir surface area of hydropower station are set refer to the actual situation of hydropower generation in a southwest province.

During an operating day, the lowest system demand appears at 4 am which is 992 MW, and the highest demand is 2310 MW that is at 5 pm. According to the day-ahead market clearing result, the thermal power 1 as well as hydropower 1 and 2 which have low bidding price are reaching the output upper limit at most of the time. The thermal power 2,3 and 4 which have high bidding price are mainly responsible for power balance during the peak time. When demand is over 1100MW, which is the sum of the output upper limits of the thermal power 1, hydropower 1 and 2, the rest of the generators are scheduled in merit order depending on their bidding price.
As the system does not exist any congestion, the clearing price of each node is the same which equates to the bidding price of the marginal power unit. The changes of the system demand and marginal clearing price during operating day are shown below.

![Fig. 3 system demand and marginal clearing price for basic scenario](image)

In the basic scenario, the inflow of the river is always sufficient for hydropower 1 and 2 to maintain the maximum generation output.

4.3 The scenario with insufficient inflow

![Fig. 4 the clearing result of the scenario with insufficient inflow](image)
In this scenario, the expectation of nature inflow of the river is reduced, which cannot ensure that the hydropower generators maintain at the output upper limits. The objective of the market clearing model is to optimize the generation cost of the system. Although the nature inflow of the river is low, hydropower 1&2 can still increase the output through the decrease of the reservoir storage and try to maintain at the maximum output levels. However, because of the water level control constraint, the storage of the reservoir cannot be reduced unlimitedly. Therefore, the optimal arrangement of hydropower generators is made according to the all-day load demand. It is beneficial to reduce the marginal prices during high demand period, when the hydropower generators produce more power during that period. Based on the clearing result, it shows that at 12pm of the operating day, both the water levels of the hydropower 1 and 2 reach the lower limits, and it has maximized the role of existing storage capacity.

4.4 The scenario with higher bidding price for hydropower 2

Based on the first scenario, it is assumed that the quotation of hydropower 2 is increased to 550 ¥/MWh, which has exceeded the quotations of thermal power 1, 2 and 3, and its power generation schedule should be reduced. The maximum output of the combination capacity among thermal power 1 to 3 and hydropower 1 is 1800MW, which is less than the system load demand during 3pm to 6pm and 8pm. As a result, hydropower 2 must be arranged for these periods. In addition, the output of hydropower 2 at 1 am and 7 am is also not zero, which is caused by the limitation of the ramping rate of thermal power units.

Before 1 am, thermal power 1 to 4 are running at minimum technical output level, which the sum of them is 590 MW. At 1 am, hydropower 1 that has the lowest bidding price is first arranged to its maximum output level, which is 500 MW. Then thermal power 1 to 3 that have relative low bidding prices increase generation outputs with their maximum ramping rates, and reach 200 MW, 450 MW and 270 MW respectively. Thermal power 4 that has highest bidding price is shut down, whose output decreases from 170 MW to 0. The shortage between the load demand (1505 MW) and the sum of all power generation capacities except the capacity of hydropower 2 (1420 MW) is 85 MW, which can only be supplied by hydropower 2.

At 7 am, Three of the four power generators (thermal power 1, 2 and hydropower 1) whose bidding price is lower than hydropower 2 have already operated at its output upper limits. The total output of these three generators is 1450 MW, and it still has a 55 MW shortage between supply and demand which should be supplied by the rest of the thermal power 3. However, thermal power 3 is shut down during 2 am to 6 am. If it starts up at 7 am, it has a minimum technical output of 120 MW, which will reduce the output of other generators that has lower generation cost and eventually cause the increase of the total generation cost. Therefore, from the perspective of global optimization, the power shortage at 7 am is supplied by hydropower 2 with a slightly higher bidding price but flexible start-up. If the quotation of hydropower 2 is further adjusted to 600 ¥/MWh, thermal power 3 will be started up at 7 am.
In this scenario, there is a large amount of natural inflow, and the low-priced upstream hydropower station 1 operates at full output state throughout the day, resulting in a large inflow of hydropower station 2. However, hydropower 2 wins fewer bids. As a result, excess water had to be stored in reservoirs or abandoned.

If the water level constraint of the reservoir is being approached, the volume of abandoned water increases and cannot ensure the consumption of the renewable energy. In order to solve this problem, the following two solutions can be adopted: firstly, the abandoned water caused by overprice is not included in the statistics, which has been precedent in Gansu, Shanxi and other provinces; Secondly, include the policy constraint in the clearing model, which means that the penalty function for energy abandonment is added to the objective function, so as to reduce the amount of water discarded in the clearing result as far as possible.
5. Conclusion
In this paper, a day-ahead market clearing model with fair participation of cascade hydropower stations is proposed, which alleviates the imbalance of hydropower matching caused by information opacity, improves the feasibility of day-ahead power generation plan, and provides a reference to establish market mechanism for hydropower consumption in the areas that is rich in hydropower resources. However, in this model, the power output characteristics and water level capacity curve of hydropower station have not been precisely considered. In order to produce a better power generation schedule, further research is needed.

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