Research on bidding mechanism and strategy of hydropower unit based on coupling resources

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Abstract. The construction of the electric power spot market in China is at an initial stage, and there is a contradiction between the bidding mode of single-unit bidding and the physical operating characteristics of cascade generating units. When all generators in the market make price declarations and settlements independently, the dispatching and clearing results may violate the operating performance of the actual units, bring difficulties to the unit joint bidding, and at the same time cause serious deviations in scheduling and waste of actual resources. Therefore, for the power generation resources coupled with resources such as cascade hydropower units, this paper proposes a bidding mechanism based on aggregation nodes. First, the bidding mechanism and bidding strategy of the aggregation node is introduced in detail, and then the spot market-clearing model of the aggregation node bidding is established. Finally, the IEEE5 simulation shows that the bidding mechanism based on the aggregation node can make the market-clearing result reflect the unit’s willingness to trade, effectively allocate cascade hydropower generation resources, and improve market transaction efficiency.

1. Introduction
China actively advances electricity spot market transactions [1], and each spot pilot province in China adopts the location marginal price (LMP) pricing method [2, 3]. In the spot market, units generally have their output power and electricity price settled according to a single node. However, this mechanism is in contradiction with the physical operating characteristics of cascaded generator sets, which makes it difficult for units with resource coupling characteristics to efficiently and reasonably conduct market biddings and transactions. The separate bidding mechanism will make market-clearing results infeasible [4-6] which may require the second adjustment. In that case, it will cause damage to the interests of power generation entities and waste of resources, which is not conducive to the efficient and optimized allocation of resources.

For the reason of inefficiency, some literature provides the design of market mechanisms for such coupled-constrained fleets. Ref [7] optimizes the combination of multiple gas-fired units, but bring to the problem of curse of dimensionality due to excessive constraints, which is difficult to implement in the actual clearing rules. Ref [8] designed a mechanism for cascading hydropower to participate in the day-ahead market, but the mechanism provided can’t reflect the hydraulic coupling relationship between upstream and downstream power stations efficiently. Ref [9] design a competition mode between hydropower and thermal power and provide solutions that can provide a reference for the construction of the power market in China. Ref [10] proposed a market bidding model for flexible
block trading, which can meet the trading needs of resource-coupled units to a certain extent. Ref [11] further combines the Chinese spot market to construct a market-clearing model that considers flexible block transactions, but this model design will bring higher computational complexity to the market-clearing.

The paper proposes a bidding mechanism based on aggregation nodes. Through the aggregation of nodes to unify the bidding of the unit joint, the power generation bidding mechanism can effectively simplify the internal model constraints of the cascaded hydropower, reduce the complexity of clearing, which is more feasible in practice. Moreover, the bidding mechanism can better meet the power generation technical characteristics of the coupled units, and has less incentive to change the commitment or dispatch, thereby making the power transaction process more efficient and flexible.

2. Hydropower aggregation bidding mechanism and its bidding strategy
The location information of the clearing node in the spot market is the key information that affects electricity generation and consumption. The domestic electricity market node corresponds to a physical address, and the generation side and the demand side will make separate biddings and settlements based on the corresponding node. However, in reality, generators may act as agents for multiple units located at different nodes at the same time, and there may be some physical coupling relationship between units. Single-node biddings may increase the difficulty of unit strategy because the result of market-clearing does not meet the actual power plant operating requirements.

Therefore, a bidding product for coupled units should be designed. According to the upstream and downstream coupling characteristics of hydropower resources, and concerning advanced foreign experience models, the aggregate bidding mechanism can better meet the power generation technical characteristics of the coupled units, thereby making the power transaction more efficient and flexible.

2.1. Power generation aggregation bidding mechanism
The coupled units corresponding to the aggregated bidding can jointly submit the same bidding, which is equivalent to "one unit" participating in the spot market. The market-clearing result corresponds to the unified scheduling plan of the unit joint. Therefore, the entire hydropower unit joint will be successfully cleared out as a whole, and vice versa.

Besides, the aggregate bidding needs to additionally submit joint generation distribution factors (GDFs) to represent the expected proportion of each unit in the aggregate resource. The unified dispatch plan of the aggregated bidding will be specifically allocated to each generator according to GDFs. The GDFs can correctly and effectively convey the coupling information between power generation resources, and avoid the uncoordinated dispatch caused by the single-node biddings.

In general, the coupling relationship between resources is relatively fixed during the period in the spot market. To simplify the bidding of units, a default generation distribution factor (GDFs) can be generated for each aggregated generation resource based on information such as the maximum capacity or historical power generation.

2.2. Hydropower aggregation bidding strategy
Compared with thermal power units, the bidding strategy of hydropower units is more complicated. Because hydropower may realize energy storage through reservoir storage, the time span of hydropower dispatch is longer than thermal power units, which means that hydropower dispatch has time coupling characteristics [12].

Therefore, the cost of hydropower includes not only the relatively fixed costs to maintain the operation of the units but also the opportunity cost represented by "peak shaving and valley filling" of power generation [13, 14]. Specifically, the opportunity cost of hydropower depends on the future net inflow of the reservoir, the load power, and the strategy of other power generation companies. These factors are usually unknown [12]. Hydropower companies need to actively integrate their own costs, as well as studying the profit opportunity during peak and valley periods of the market to determine their bidding decisions.
Also, the GDFs of cascade hydropower needs to comprehensively consider factors such as the proportion of water area flow of all levels of hydropower, the proportion of historical power generation, and the generation capacity of all units. The purpose of GDF settings is to improve the feasibility of the market-clearing.

3. Aggregate bidding model

3.1. Objective function

The objective function of the scheduling model is to minimize the operating cost of all units in the whole period.

$$\min F = \min \left( \sum_{t=1}^{T} \sum_{i=1}^{I} C_i \left( p_i(t) \right) \right)$$  \hspace{1cm} (1)

In the formula, $F$ represents the operating costs of all units in the whole period. $T$ is the number of time periods, and $I$ is the number of units considered for optimization. $C_i \left( p_i(t) \right)$ represents the variable cost of unit $i$ in period $t$. $p_i(t)$ represents the active power output of unit $i$ in period $t$.

3.2. System real power balance constraints

$$\lambda(t) : \sum_j p_j(t) = \sum_j d_j(t), \hspace{1cm} t = 1,2,...,T$$  \hspace{1cm} (2)

In the formula, $d_j(t)$ represents the load of node $j$ in period $t$. $\lambda(t)$ is the shadow price of the power balance constraint.

3.3. Units operating constraints

$$\bar{\varepsilon}_i: p_i \leq \bar{P}_i$$  \hspace{1cm} (3)

$$\underline{\varepsilon}_i: p_i \geq \underline{P}_i$$  \hspace{1cm} (4)

Where $\bar{P}_i$ and $\underline{P}_i$ are the maximum and minimum capacity of unit $i$. $\bar{\varepsilon}_i$ and $\underline{\varepsilon}_i$ represents the shadow price of unit operating constraints (3)(4).

All units in aggregated unit joint $\Phi$ are constrained as follows. The unit joint is bundled as single-unit bidding which means that their operating state variables are the same.

$$y_{i1\in\Phi}(t) = y_{i2\in\Phi}(t) = \cdots = y_{in\in\Phi}(t)$$  \hspace{1cm} (5)

$$y_i(t) \in \{0,1\}$$  \hspace{1cm} (6)

When $y_i(t)$ is 0, it means that unit $i$ is shutdown during period $t$, and when $y_i(t)$ is 1, unit $i$ is online during period $t$.

3.4. Network transmission constrains

$$\bar{\mu}_i(t): p_i(t) \leq \bar{P}_i$$  \hspace{1cm} (7)

$$\underline{\mu}_i(t): p_i(t) \geq \underline{P}_i$$  \hspace{1cm} (8)

In the formula: $p_i, \bar{P}_i, \underline{P}_i$ respectively represent the power flow, power upper limit, and lower limit of the branch $l$; $\bar{\mu}_i(t)$ and $\underline{\mu}_i(t)$ are the shadow price of constraints (7)(8).

3.5. Aggregate biddings

The aggregate unit joint $\Phi$ submits the same gradient bidding including the electricity capacity, electricity price, and the distribution coefficient within the unit joint. Suppose $p_\Phi$ is the cleared power of the aggregate biddings and the distribution coefficient of unit $i$ is $\varphi_i$.

The cleared power of unit $i (i \in \Phi)$ is:

$$p_i \in \Phi = p_\Phi : \varphi_i$$  \hspace{1cm} (9)

3.6. Out-of-market constraints

The operation of the cascade power station joint takes into account the upstream and downstream time lag [15] and constraints of each power station’s storage capacity, water flow constraints, and unit capacity. Such factors will not be considered in the power spot market. This article only considers
such constraints in the scheduling scheme as a reference standard for separate biddings in the spot market and aggregate node biddings.

4. Case study and results

Based on the IEEE5 case shown in Figure 1, the initial state of the system operation is set. The unit joint for aggregated bidding includes several cascaded hydropower stations with three levels located in the same river basin. There is a coupling relationship between the power generation of the upstream and downstream.

To simplify the model, this calculation case simplifies the constraints between the cascade power stations and set the water flow ratio between the three power stations 1, 4, and 6 in the cascaded hydropower joint as 1:0.6:0.5.

![Figure 1. 5-node system model.](image1)

It is assumed that units 1, 4, and 6 are cascaded hydropower units in the same river basin, and the remaining units are thermal power units. The number of bidding segments is 5, which affects the market optimization of 96 points in a day. After considering the coupling constraints between hydropower units, the ratio of the water flow between the three is about 1:0.6:0.5. In the day-ahead market, the cascaded hydropower joint may adopt different bidding strategies. Assume that non-hydro power generating units in the market are bidded at their true cost and hydropower generating units bid at opportunity cost.

While considering the simplified constraints within the cascade hydropower stations, an optimized reference dispatch plan can be derived as shown in Figure 2 below.

![Figure 2. Hydropower units output in reference clearing model.](image2)

4.1. Analysis of results of separate bidding strategy

When cascading hydropower groups are bidding separately according to their respective maximum generation capacity and the market-clearing does not consider the internal constraints of cascade
hydropower, the market-clearing situation can be obtained. To simplify the analysis, the water flow and power generation can be simply assumed as linear correlation assumptions. The separate bidding strategy is shown in Table 1.

Table 1. Hydropower unit different bidding strategies (bidding separately).

| block | Power/(MW) | Unit   | Price/($/MWh) |
|-------|------------|--------|---------------|
| 1     | 40         | Unit 1 | 11            |
|       | 20         | Unit 4 | 12            |
|       | 20         | Unit 6 | 14            |
|       | 30         | Unit 1 | 21            |
| 2     | 20         | Unit 4 | 22            |
|       | 20         | Unit 6 | 24            |
|       | 20         | Unit 1 | 31            |
| 3     | 20         | Unit 4 | 32            |
|       | 10         | Unit 6 | 34            |
|       | 15         | Unit 1 | 41            |
| 4     | 15         | Unit 4 | 42            |
|       | 10         | Unit 6 | 44            |
|       | 15         | Unit 1 | 51            |
| 5     | 5          | Unit 4 | 52            |
|       | 10         | Unit 6 | 54            |

In this bidding strategy, all units are bidded based on their marginal cost. Ignoring the constraints outside the market, the clearing result in Figure 3 can be obtained.

Figure 3. Comparison of clearing results of Cascade Hydropower Units 1.

In the actual situation, due to the internal constraints of the cascaded hydropower system, some of the hydroelectric units cannot be cleared and out-of-market dispatch needs to be performed. The hydropower adjustment deviation can be obtained as shown in Figure 4.
Figure 4. Deviation between hydropower clearance and actual optimization (bidding separately).

It can be seen that hydropower unit 1 has a lot of power waste, and hydropower unit 2 and unit 3 will decrease the output.

4.2. Analysis of aggregated bidding strategy results

In this bidding strategy, all hydropower units are collectively regarded as a "large unit" for bidding. The bidding strategy is shown in Table 2. The aggregate bidding distribution ratio coefficient is initially set to 1: 0.6: 0.5, which can actually be adjusted more accurately in real time. Ignoring the constraints outside the market, the clearing result in Figure 5 can be obtained.

Table 2. Hydropower unit different bidding strategies (bidding aggregately).

| block | Power/(MW) | Price/($/MWh) |
|-------|------------|--------------|
| 1     | 80         | 12           |
| 2     | 70         | 22           |
| 3     | 50         | 32           |
| 4     | 40         | 42           |
| 5     | 30         | 52           |

Figure 5. Comparison of clearing results of Cascade Hydropower Units 2.

Different from the situation where each hydropower group makes bidding separately, the clearing result of the aggregate bidding can meet the external constraints of the cascaded hydropower. Comparing the hydropower regulation under the reference situation, the regulation deviation can be obtained as shown in Figure 6 below.
Figure 6. Deviation between hydropower clearance and actual optimization (bidding aggregately).

It can be seen that there is a certain amount of deviation between the individual hydropower units when aggregated bidding, but the overall deviation of the whole unit is lower than the case of separate biddings. Therefore, aggregated bidding can simplify the constraints of cascade hydropower in the model and ensure that its feasible solution is closer to the reference solution.

4.3. Comparison of different bidding models

The income of market participants under different bidding models is shown in Table 3. It can be seen that in the case of separate bidding, due to the physical coupling nature of the cascade hydropower, there are constraints on the upstream and downstream hydropower generators, and the separate bidding cannot guarantee the price. The cleaning result meets the actual operating conditions, so additional dispatching is needed to adjust the power generation. In the case of aggregate bidding, the clearing situation can meet internal requirements, and the amount of electricity adjustment is extremely low. Besides, the cleared output power of hydropower is larger, which can increase the revenue and reduce the amount of hydropower loss.

Table 3. Comparison of different bidding strategies.

| Situation          | Clearing Power/MW | Generation Adjustment/MW | Total cost/$   | Total revenue/$ | Revenue /$ | Electricity loss /MW |
|--------------------|-------------------|--------------------------|----------------|-----------------|------------|----------------------|
| bidding separately | 4247.69           | 357.87                   | 187327.64      | 44879.69        | 16859.76   | 29.9                 |
| bidding aggregately| 4253.43           | 12.8                     | 187327.64      | 47549.5         | 19660      | 6.9                  |

Since market entities cannot accurately predict the biddings of other generating units and the LMP of the node where they are located, adopting a separate bidding strategy is likely to cause the actual clearing output which doesn’t meet the generation coupling constraints within the unit group. Therefore, in the real-time market, additional power generation adjustments are required, and higher-cost power generation resources are likely to be used for power balance which not only increases the complexity of dispatching work but also increases system operating costs.

The aggregated bidding can effectively simplify the model constraints to solve the complex constraints within the actual cascade hydropower. Besides, the aggregated bidding mechanism can better reflect the coupling relationship of the fleet, reduce the complexity of clearing, and reduce the total cost of power generation.

5. Conclusions

This paper proposes a bidding mechanism based on aggregation nodes and establishes a mathematical clearing model for aggregation biddings. The following conclusions are drawn through the simulation of IEEE5 nodes: 1) The power generation and load biddings in the electricity market should summit the aggregated resource biddings and the corresponding distribution factor, which integrates the
methods of locational marginal prices and regional biddings, better meets the power generation technical characteristics of coupled units, reflects the willingness of units to trade, and a certain extent ensures the flexibility of resource bidding. The efficiency and accuracy of resource utilization are improved; 2) The bidding of the unit joint is unified through the aggregation node. The generation bidding mechanism of the aggregation node can efficiently simplify the internal model constraints of the cascaded hydropower, ensure the feasibility of the clearing result, and reduce the complexity of mathematical model clearing.

However, the aggregate bidding does not consider the hydraulic time lag constraint because the distribution coefficient is the same in each period which can make improvements in future research.

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