Single-time power frequency modulation and peak-modulation market combined clearing method considering new energy absorption capacity

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Abstract—In order to support the transaction clearing business of power frequency modulation and peak load modulation market in China and improve the absorption capacity of new energy, the coupling relationship between power frequency modulation and peak load modulation auxiliary service is studied, and the combined clearing method of single time period power frequency modulation and peak load modulation market considering the absorption of new energy is proposed. The coupling relationship between power frequency modulation and peak power modulation auxiliary services is reflected in that the two auxiliary services are mutually exclusive. Considering the important promoting effect of peak regulation capacity on new energy consumption, the index of residual depth peak regulation capacity was proposed as the evaluation basis of the clearance result on new energy consumption capacity. On this basis, a single time combined clearing model of power frequency modulation and peak-shaving market is constructed, which takes the minimum clearing cost as the main optimization objective and the maximum remaining peak-shaving capacity as the secondary optimization objective. Numerical examples show that the proposed method has significant advantages over the current sequential cleaning method and the combined cleaning method without considering the consumption of new energy in terms of transaction cost and residual depth peak-shaving capacity. The results show that the method proposed in this paper meets the requirements of promoting the construction of new power system with new energy as the main body in China, and has significant benefits in promoting the reform of power market and improving the consumption of new energy.

1. Introduction

Power auxiliary service is a necessary operation resource of power grid dispatching operation. In recent years, with the deepening of China’s power market reform, the power auxiliary service market has become the focus of the reform. Power frequency modulation and power peak modulation auxiliary service market are the main contents of power auxiliary service market [1-2].

Power peak shaving is a special power auxiliary service in China, which is used to provide economic compensation for the deep peak shaving provided by traditional power sources such as coal and gas that are below their minimum technical output, and for the peak shaving provided by traditional power sources that are restarted after shutdown to meet the requirements of supply-demand balance [3]. Since the northeast China regional power grid took the lead in constructing and operating the peak shaving auxiliary service market in 2013, the north China, northwest China, Shanxi, Guangxi and other provinces and regions have established the peak shaving auxiliary service market [4-6]. At present, the peak load shaving market in each province generally includes pre-clearing before the day
and formal clearing within the day. Taking the minimum peak load shaving compensation as the optimization goal, the peak load shaving market clearing model is established by comprehensively considering the constraints such as peak load shaving capacity and clearing order of units. The above clearing model is centralized clearing in nature. In order to further tap the peak regulation potential of market members and promote the solution of new energy consumption under the insufficient peak regulation capacity, a bilateral peak regulation market transaction mechanism for new energy consumption is proposed in reference [7].

The power frequency modulation market is used to conduct the secondary frequency modulation resource market transaction of the power grid, so as to determine the secondary frequency modulation auxiliary service provider of the system [8]. Foreign mature power markets such as PJM in the United States have carried out frequency modulation market trading. In recent years, to meet the development needs of new formats such as energy storage, frequency modulation market trading rules have been constantly improved, and energy storage power plants have been considered to participate in frequency modulation market [9]. Power grids in southern China and eastern China have also established frequency modulation auxiliary service markets. In addition, the transaction mechanism and operation control technology in frequency modulation market, such as dc connection line between interconnected power grids and integrated fire storage system, have also been extensively studied.

All kinds of auxiliary services, such as electric energy and peak and frequency regulation, have the characteristics of coupling in operation, so the connection relationship of the above trading variety clearing mechanism must be considered in the design of market mechanism. Literature [10] studied the connection problem of clearing mechanism of electric energy, frequency modulation and other trading varieties, compared the difference between sequential clearing mechanism and joint clearing mechanism, and concluded that the implementation of sequential clearing mechanism is relatively simple, but it will affect the declaration of market subjects due to the difference in opportunity cost. Peak regulation and frequency regulation are the two most widely used auxiliary service trading varieties in China. At present, the order clearing mechanism is mainly adopted. Generally, the market clearing of frequency regulation auxiliary service is preferentially carried out, and the result is regarded as the boundary requirement of peak regulation market clearing [10]. The above order clearing mechanism also faces similar problems and is prone to speculation by market members.

Therefore, this paper will study the power frequency modulation and peak modulation market combined clearing method, in order to solve the above order clearing mechanism of market speculation. Firstly, the power frequency modulation and peak load modulation market clearing models are introduced, and the coupling relationship between the two auxiliary services is analyzed. Then, considering the effect of clearing results on the absorption capacity of new energy, a joint clearing model considering the absorption capacity of new energy is proposed. Finally, an example is constructed based on the actual grid data of a province to verify the effectiveness of the proposed method.

2. Coupling characteristic analysis

2.1. Analysis of coupling characteristics
The coupling relationship between power peak modulation and power frequency modulation is reflected in the limitation of the generator set's own performance. When the generator set is lower than its minimum technical output to provide in-depth peak modulation auxiliary service, it generally does not have the ability to input automatic generation control function, that is, it cannot provide power frequency modulation auxiliary service. Affected by this characteristic, for any generator set, it is mutually exclusive to participate in the power peak modulation auxiliary market and power frequency modulation auxiliary service market, that is, only one generator set can participate in the power frequency modulation or power peak modulation market at any time.

It is because of the mutually exclusive characteristics of power peak modulation and power frequency modulation auxiliary services that the connection of power peak modulation and power
frequency modulation auxiliary services must be considered when the power grid of a province carries out the market transaction clearing of power peak modulation and power frequency modulation auxiliary services.

2.2. Design of residual depth peak shaving ability evaluation index

The peak regulation capacity of power grid is closely related to the consumption of new energy. Due to the outstanding problem of new energy anti-peak regulation, the lack of peak regulation capacity is the key factor limiting the consumption of new energy. According to statistics, wind abandoning and light abandoning power caused by insufficient peak regulating capacity accounts for more than 30% of China's total wind abandoning and light abandoning power [6]. Therefore, this paper takes the residual depth peak-shaving capacity corresponding to the clearing result as the evaluation index of new energy consumption capacity. The so-called remaining depth peak adjustment capacity refers to the sum of the remaining deep peak adjustment capacity of the generator set after the loss of part of the deep peak adjustment capacity of the whole network due to the bidding of part of the generator set for power frequency modulation auxiliary service, which can be expressed as:

\[
R_{Re} = \sum_{g=1}^{NG} (\lambda^F_g - 1)(R^P_{g,\max} - R^P_g)
\]

where \( R_{Re} \) is the evaluation index of residual depth peak adjustment capacity proposed in this paper. \( R^P_g \) is the bid-winning capacity of generation unit \( g \) in peak adjustment market. \( R^P_{g,\max} \) is the maximum value peak adjustment capacity of generator set \( g \). \( NG \) is the number of generator sets in the whole network. \( \lambda^F_g \) is the state variable of whether the generator set is bid-winning or not. The formula indicates that if a generator set wins the bid for power frequency modulation auxiliary service market, i.e. \( \lambda^F_g = 1 \), the remaining depth peak adjustment capability will be eliminated in the statistics of remaining depth peak adjustment capability evaluation index. Meanwhile, the bid-winning peak load adjustment capacity of each generator set will be eliminated in the statistics of remaining peak load adjustment capacity.

3. Combined cleaning method considering the absorption capacity of new energy

In essence, the combined clearing model of power frequency modulation and peak modulation auxiliary service market is a programming problem aiming at the lowest transaction clearing cost. However, due to the mutual exclusion of the two auxiliary service varieties, if only transaction clearing cost is considered, the model has the feature of multiple solutions, that is, the optimal transaction clearing cost may correspond to multiple clearing methods. Therefore, the main purpose of the joint clearing model is to screen out the clearing scheme that is most beneficial to the operation of the power grid according to the multi-solution of the joint clearing model and the absorption capacity of new energy as the standard.

According to the above analysis of the mutual exclusion between power frequency modulation and power peak modulation, this paper will build a joint clearing model considering the absorption capacity of new energy. The objective function of the clearing model includes three parts:

(1) Clearing cost of power frequency modulation market;
(2) Clearing cost of power peak shaving market;
(3) Absorption capacity of new energy, that is, peak adjustment capacity of residual depth corresponding to clearing result.

In the design of constraint conditions, in addition to the existing constraint conditions of the single clearing model of power frequency modulation and power peak-assisted service, the mutually exclusive relationship between power frequency modulation and power peak-assisted service should also be considered.
Based on the above analysis process, the combined clearing model of power frequency modulation and peak modulation market considering the absorption capacity of new energy can be expressed as:

$$\begin{align*}
\text{Min } & \alpha^P \sum_{g=1}^{NG} p_g^P \tilde{R}_g^P - \alpha^E \sum_{g=1}^{NG} \lambda_g^E P_g^E \\
& + \alpha^P \sum_{g=1}^{NG} p_g^P \tilde{R}_g^P - \alpha^E \tilde{R}_g^E \\
\text{s.t. } & \sum_{g=1}^{NG} R_g^F \geq R_{F, set} \\
& R_g^F \leq R_{g, max}^F \\
& (\lambda_g^F - 1) R_g^F = 0 \\
& \sum_{g=1}^{NG} R_g^P = R_{P, set}^P \\
& R_g^P \leq R_{g, max}^P \\
& (\lambda_g^P - 1) R_g^P = 0 \\
& \lambda_g^P + \lambda_g^F \leq 1
\end{align*}$$

(2)

where $NG$ is the number of generator sets in the whole network. $R_g^P$ is biding capacity of generation unit $g$ in peak load regulating market. $p_g^P$ is declare price for peak load regulating capacity of the generation unit $g$. $R_g^F$ is the bid-winning capacity of generation unit $g$ in frequency modulation market. $p_g^F$ is declare price for frequency modulation capacity of the generation unit $g$. $\lambda_g^F$ is the state variable of whether the generator set is bid in the power frequency modulation market. $\lambda_g^P$ is the state variable of power peak shaving auxiliary service market for generator set. $P_g^F$ is the comprehensive performance index of frequency modulation of the generator set. $\sum_{g=1}^{NG} p_g^P \tilde{R}_g^P$ represents clearing costs for power peak shaving market transactions. $\sum_{g=1}^{NG} p_g^F R_g^F$ and $\sum_{g=1}^{NG} \lambda_g^E P_g^E$ are respectively the clearing cost of power frequency modulation market and the comprehensive performance of bid-winning units. $\alpha^P$ and $\alpha^E$ is respectively the weight coefficient of the optimization target item of power peak shaving clearing cost and remaining depth peak shaving capacity. In order to ensure that the cleaning results meet the requirements of minimum cleaning cost and optimal frequency modulation performance, it should be satisfied $\alpha^F, E \gg \alpha^F, P$. $\alpha^P$ and $\alpha^E$ are respectively the weight coefficient of the optimization target item of power peak shaving clearing cost and remaining depth peak shaving capacity. $R_{F, set}$ is frequency modulation capacity requirements for grid operation. $R_{g, max}^F$ is the maximum frequency modulation capacity of the generator set. $R_{P, set}$ is peak capacity requirements for grid operation. $R_{g, max}^P$ is the maximum peak load regulating capacity of the generator set.
4. Case study

In this paper, an example is constructed on the grid of a province to verify the effectiveness of the proposed method. A total of 12 generator sets were designed, with a total installed capacity of 4500MW. The minimum technical output of each generator set is 50% of its installed capacity. The generator sets have a combined maximum frequency modulation capacity of 55MW and a combined maximum peak-modulation capacity of 49MW.

According to the combined clearing method proposed in this paper, the calculation example will first evaluate the depth peak regulation requirements and frequency regulation requirements. According to the transaction rules of the provincial power grid frequency modulation market, the frequency modulation capacity is 3% of the forecast of unified load regulation in this period, and the deep peak modulation demand is the difference between the minimum technical output of all generating sets and the generation demand after deducting the generation demand of new energy. According to the above calculation rules and combined with the actual power grid data of the province, the frequency modulation capacity requirements in the test period of the example are 18MW respectively. Peak regulation capacity requirement is 5MW.

As shown in Table 1 above, clearing results show:

1. The sum of the bid-winning capacity of the generator set in the frequency modulation market and peak modulation market at each time period just meets the capacity demand of the power frequency modulation and peak modulation market. The reason for the above clearing result is that the joint clearing model is a minimization and optimization scale model. On the basis of meeting the capacity demand of the power frequency modulation and peak modulation market, As a result, clearing arrangement will preferably be carried out in a way that exactly meets the demand of frequency modulation and peak regulation.

2. The bidding conditions of generating units in the power frequency modulation and power peak modulation markets in each period are mutually exclusive, that is, the bidding can only be won in one market at most at any time, and this bidding method meets the requirements of the lowest transaction costs in the market;

3. The absorption capacity of new energy and the frequency modulation performance of generating units are the key factors to determine the bidding sequence of generating units under the condition of the same transaction clearing cost. Although generator set 10, generator set 11, and...
generator set 12 have the same declared prices in the power frequency modulation market and the power peak modulation market, generator set 10 is preferentially cleared as a frequency modulation set due to its more outstanding frequency modulation performance.

5. Conclusions
In order to realize the combined clearing of power frequency modulation and power peak modulation auxiliary service, and ensure that the clearing results meet the requirements of new energy absorption, this paper proposes a combined clearing method of power frequency modulation and peak modulation market considering the absorption capacity of new energy. In order to improve the overall peak-shaving capacity of cleaning results, the assessment item of new energy consumption capacity with residual peak-shaving capacity as evaluation index was proposed in the combined clearing model. This method is in line with the requirements of China's current construction of new power system with new energy as the main body, and has significant benefits in promoting the reform of power market and improving the consumption of new energy.

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