Based on the Reliability Option: A New Mechanism Design Method for Power Generation Capacity Adequacy

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Abstract. With the deepening of power market reform, the issue of power generation capacity adequacy has become increasingly prominent. To address this issue, this paper proposes a new mechanism design method for power generation capacity adequacy based on reliability options. Through steps such as parameter determination, entity bidding, auction clearing, contract signing, and price difference settlement, this method aims to optimize the allocation of the power market. Additionally, this paper discusses the constraints in the auction clearing process of reliability options and verifies the effectiveness of this method through case analysis.

Keywords: reliability option, power generation capacity adequacy, auction clearing

1 INTRODUCTION

In the context of the power market, ensuring the adequacy of power generation capacity is an important aspect of market design. The main reasons for designing a separate power generation capacity adequacy mechanism are: on one hand, the volatility of market prices and policy uncertainties after market operation increase the risk of power generation investment, affecting power generation investment; on the other hand, electricity, as a basic production and living material, often has its price strictly regulated and is influenced by many policies, which can create a discrepancy between market prices and their true value[1]. Some scholars use the terms "missing market" and "missing money" to illustrate these issues. In power systems dominated by new energy sources, the large fluctuations in output and the randomness of wind and solar power generation exacerbate these problems. Internationally, typical power shortages and blackouts such as the 2001 California power outage have prompted academic and industrial attention to power generation capacity adequacy in the power market environment. In China, with the deepening of market construction[2], changes in supply and demand, and changes in power source structure under the "dual carbon" goals, the issue of power generation capacity adequacy has attracted increasing attention[3].

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Power market reform is an important direction for the development of the power industry, but the issue of power generation capacity adequacy has gradually emerged during the reform process. Power generation capacity adequacy refers to the ability of the power system to meet load demand while having a certain amount of spare capacity to cope with emergencies[4]. To ensure the safe and stable operation of the power system and improve market efficiency, this paper proposes a new mechanism design method for power generation capacity adequacy based on reliability options.

2 CHARACTERISTICS OF RELIABILITY OPTION MECHANISM

There are various mechanisms and methods to ensure power generation capacity adequacy in a market environment, including scarcity pricing mechanisms and capacity market mechanisms. The scarcity pricing mechanism is suitable for systems with relatively complete market mechanisms and fewer price distortions due to policies or market mechanisms. The main problem is that when there are significant changes in power supply and demand, the price fluctuations in the spot market can be quite large, requiring related mechanisms and tools to help market entities hedge and reduce risks, and it also places high demands on the risk management capabilities of market entities[5].

The capacity mechanism is relatively stable and can make market prices more stable, which is a mechanism favored by many regulatory mechanisms and many power generation companies. Its problems include: the capacity compensation price or capacity demand needs to be determined by the market operation entity, which may lead to overcompensation and increase the overall power supply cost; the existence of capacity compensation can distort energy market prices and, in some cases, restrict the entry of new investments.

The "reliability option + energy market" mechanism can be combined with the scarcity pricing mechanism, and through positive price difference returns, it protects the income stability of both the generation and consumption sides, fully reflects the system supply and demand in real-time electricity prices, correctly guides power generation investment, and makes the social value of power capacity more clear and transparent, improving the efficiency of the power market. This paper first introduces the principles of the reliability option mechanism and then analyzes the important modules for implementing this mechanism[6].

2.1 Basic Principles of Reliability Options

The power generation capacity adequacy mechanism based on reliability options integrates the characteristics of scarcity pricing, capacity market, and options. The main features and basic principles are as follows:

a) Similar to a centralized capacity market, the market operation entity determines the capacity demand in the forward market to determine the number of reliability options.

b) The market operation entity organizes the auction of reliability options to determine the option price. The overall auction process is similar to the centralized capacity market, but there are differences in specific auction mechanisms.

c) The main difference from the capacity market lies in the settlement mechanism: the capacity that wins the bid in the reliability option receives an option fee similar to capacity compensation, but the positive difference in the spot market price above the execution price must be returned to the market operation entity.

d) The reliability option mechanism can be combined with the scarcity pricing mechanism, setting a scarcity price increment or not setting a price cap.

2.2 Market Composition

The reliability option mechanism can be considered a supporting mechanism for the energy market, with the trading product being the reliability option contract[7]. The sellers of the options are capacity resources, including in-zone (out-of-zone) power generation units, demand response resources, and energy storage operators. Capacity resources can be voluntary or mandatory participation. Buyers can be market operation entities (centralized) or load service entities (decentralized). The option insurance fee (referred to as "premium") is generally shared according to the user's proportion of peak load.

2.3 Settlement Mechanism

(1) Settlement Mechanism

Reliability options are a financial product, a type of call option. The buyer of the option pays a premium to the seller, granting the option buyer the right (not an obligation) to execute the contract at the agreed execution price (strike price) S. When the market reference price (reference price) ρ (day-ahead or balancing market price) is higher than the execution price S, the option seller must pay the positive difference in income to the buyer.

(2) Settlement Parameters

The two important parameters in the settlement mechanism of reliability options are the execution price and the reference price.

The execution price is usually announced by the system operation entity before the auction, typically based on the variable costs of the reference peak power generation unit. Generally, the market regards the execution price as a constant, but there are more complex market designs where the execution price may change over time.

The reference price of reliability options is used to reflect the actual price obtained by capacity providers when selling their power in the energy market. High prices indicate power scarcity, while low prices indicate sufficient power generation capacity. The reference price can be a combination of different markets, such as day-ahead markets, balancing markets (real-time markets), etc.

2.4 Operational Process

The flow of the Reliability Option Mechanism operation is shown in Figure 1 below:

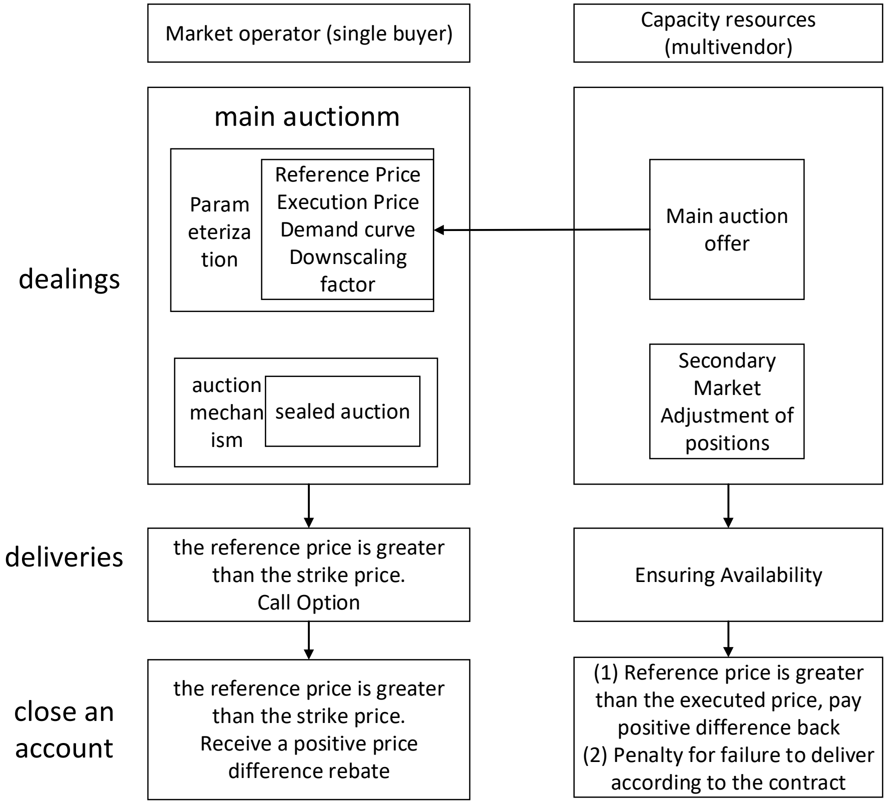

Fig. 1. Operational Process of Reliability Option Mechanism

3 DESIGN OF POWER GENERATION CAPACITY ADEQUACY MECHANISM BASED ON RELIABILITY OPTIONS

The design of the power generation capacity adequacy mechanism based on reliability options includes the following steps:

3.1 Parameter Determination

When constructing the power generation capacity adequacy mechanism based on reliability options, the precise determination of parameters is the cornerstone of ensuring the effective operation of the mechanism[8]. The setting of the execution price needs to find a balance between normal electricity prices and scarcity moment electricity prices, while ensuring that it is higher than the operating costs of power generation units to incentivize power generation investment. The setting of the total capacity demand should include peak load and an additional margin of safety to ensure the stability of the system in the face of sudden demand.

3.2 Entity Bidding

In the bidding stage, participating entities, i.e., power generation companies, must provide key information, including the unit price they are willing to accept and the power generation capacity they promise to provide. To maintain the fairness and effectiveness of the auction process, power generation companies must submit their bids within the specified bidding period and follow the principles of honesty and credit, ensuring the truthfulness and accuracy of the information provided[9]. In addition, bids should be submitted in written form and include detailed information about the company to facilitate transparency and regulation.

3.3 Auction Clearing

In the auction clearing stage, a sealed auction mechanism is used to ensure the fairness and confidentiality of the auction process. The system will determine the optimal power generation capacity allocation plan based on the price and capacity bids of power generation companies and the actual demand of the system.

3.4 Contract Signing

In the contract signing phase, contracts are signed with the winning power generation companies based on the auction results. The contract terms clearly define the rights and obligations of both parties, including but not limited to power generation capacity, price, and contract duration. For existing power generation companies, short-term contracts are provided to maintain operational continuity and flexibility; for new power generation projects, long-term contracts are provided to ensure investment returns and encourage investors to participate in the construction and development of the power market. This helps existing power generation companies adapt to market changes and policy adjustments while maintaining operational stability, and at the same time, guarantees the investment returns of new power generation projects, encouraging investors to participate in the construction and development of the power market.

3.5 Price Difference Settlement

In the price difference settlement stage, to ensure system reliability and supervision of power generation companies' performance, a price difference settlement mechanism is adopted. This mechanism considers the execution price and reference price, where the execution price needs to take into account factors such as carbon emission costs, fuel costs, and fuel transportation costs; the reference price needs to consider prices from day-ahead markets, intraday markets, balancing markets, and system services. At the same time, strict regulatory and punitive measures are implemented for default behavior, including explicit penalties, to maintain market integrity and order.

This paper not only proposes the operational process of the reliability option mechanism but also elaborates on itsobjective function, constraints, and policy constraints, forming a systematic framework for mechanism design. This helps achieve optimal allocation in the power market. These innovative points together constitute the core of the reliability option-based power generation capacity adequacy mechanism proposed in this paper, aiming to improve the efficiency and stability of the power market while providing more reliable power supply assurance for power generation companies and users.

4 RELIABILITY OPTION MECHANISM DESIGN

4.1 Objective Function of Reliability Option Mechanism

The objective function is to minimize the sum of energy cost and capacity cost. The first part represents the total capacity cost of the system, and the second part represents the total energy cost of the system. The decision variables are the capacity adequacy clearing variables of the units, the energy clearing quantity, and the unit start-stop variables.

$$\min \sum_{i\in\left\{G^{EX},G^{NE}\right\}} x_i \cdot B_i^{RO} \cdot P_i^{\max} + \sum_{i\in\left\{G^{EX},G^{NE}\right\}} \sum_{t\in T_y} y_i \cdot \left(C_{i,t}^{U} + C_{i,t}\left(Q_{i,t}\right)\right) \tag{1}$$

In the formula, T_y represents the total number of hours in a year, $C_{i,t}^{U}$, $C_{i,t}$ and $C_{i,t}^{NL}$ represent the start-up cost, energy cost, and no-load cost of the unit, respectively. B_i^{RO} represents the capacity bid of the unit. G^{EX} and G^{NE} represent the sets of existing and new units, respectively. $x_i \cdot P_i^{\max}$ represents the capacity market clearing quantity, where x_i is a 0-1 variable indicating whether the capacity is cleared, and y_i is a 0-1 variable indicating whether the unit is started, both of which must satisfy the following constraints:

$$x_i \leq y_i \tag{2}$$

4.2 Traditional Constraints

These include unit power constraints, start-stop time constraints, ramping capacity constraints, and network constraints. For virtual power plants, energy storage, and other entities, separate models and constraints need to be established.

(1) System Power Balance Constraint

$$\sum_{i\in\{G^{EX},G^{NE}\}} P_{i,t} = L_t \tag{3}$$

In the formula, L_t represents the net load of the system at a certain time period, with renewable energy generation considered as negative load included in the load.

(2) Power Constraints

$$p_{i,t} \le y_{i,t} p_i^{\max} \tag{4}$$

$$p_{i,t} \ge y_{i,t} p_i^{\min} \tag{5}$$

In the formula, $p_i^{\max}$, $p_i^{\min}$ represent the upper and lower limits of unit output.

(3) Ramping Constraints

$$p_{i,t} - p_{i,t} \le \text{V}p_i^u y_{i,t-1} + p_i^{\min}\left(y_{i,t} - y_{i,t-1}\right) + p_i^{\max}\left(1 - y_{i,t}\right) \tag{6}$$

$$p_{i,t} - p_{i,t} \le \text{V}p_i^D y_{i,t} + p_i^{\min}\left(y_{i,t} - y_{i,t-1}\right) + p_i^{\max}\left(1 - y_{i,t-1}\right) \tag{7}$$

In the formula, $\text{V}p_i^u$ and $\text{V}p_i^D$ represent the maximum ramp-up and ramp-down rates of the unit.

(4) Network Constraints

$$-p_l^{\max} \le p_{l,t} \le p_l^{\max} \tag{8}$$

The power flow constraint for lines (sections) is:

In the formula, $p_{l,t}$ represents the power flow of the line (section), and $p_l^{\max}$ represents the power flow constraint of the line (section).

(5) For virtual power plants, energy storage, and other entities, separate models and constraints need to be established.

4.3 Policy Constraints

Policy constraints include carbon emission total constraints, constraints on the clearing of certain types of units, etc. Specific constraints can be set in the reliability option auction based on the development of the power market, the actual operation of the power system, and other policy objectives.

Taking the carbon emission total constraint as an example:

$$\sum_{i\in\{G^{EX},G^{NE}\}} \sum_{t\in T} E_i^{carbon} y_{i,t} p_{i,t} \le E_{\max}^{carbon} \tag{9}$$

In the formula, E_i^{carbon} represents the carbon emission level of the unit per unit of electricity generated, and $E_{\max}^{carbon}$ represents the carbon emission total limit considering the carbon reduction policy target.

5 CASE ANALYSIS

Through the above formulas and steps, we can perform detailed calculations and analysis on the case. In the following case, The generators' offers are shown in Table 1:

Table 1. Power Generation Company Bids

Company	Price (RMB/MWh)	Capacity (MW)
A	300	100
B	280	120
C	250	150

First, calculate the total capacity demand:

T = 300MW + 0.2 * 300MW = 360 MW

Then calculate the weighted price of each power generation company:

WP_A = 300 * 100 = 30,000 RMB/MWh

WP_B = 280 * 120 = 33,600 RMB/MWh

WP_C = 250 * 150 = 37,500 RMB/MWh

Sort the power generation companies by weighted price in descending order to get the sorted list: A, B, C. Select power generation companies in turn to meet the total capacity demand T, and determine the winning power generation companies and their allocated capacity: Company B is allocated 120MW, and Company C is allocated 150MW.

In this case, by processing and sorting the bids of power generation companies, we determined the winning power generation companies and their allocated capacity. Companies B and C were allocated 120MW and 150MW of capacity, respectively. This result demonstrates the effectiveness of the reliability option-based power generation capacity adequacy mechanism in practical application, which can reasonably allocate power generation capacity to ensure the stability and reliability of the power system. Through this mechanism, the market can more effectively guide power generation investment, optimize resource allocation, and provide stable income guarantees for power generation companies and users. This not only helps improve the operational efficiency of the power market but also promotes the sustainable development of the power system.

6 CONCLUSION

This paper proposes a new mechanism design method for power generation capacity adequacy based on reliability options, achieving optimal allocation of the power market through steps such as parameter determination, entity bidding, auction clearing, contract signing, and price difference settlement. At the same time, this paper discusses the constraints in the auction clearing process of reliability options and verifies the effectiveness of this method through case analysis. This method is beneficial for eliminating market distortions, ensuring the stability of the generation and user sides, and improving market efficiency.

Of course, reliability options also have certain issues. The characteristics of different types of units vary greatly, the utilization time differences are large, and the capacity costs are significantly different. The existing reliability option mechanism assumes gas turbines as marginal units for determining the reference price, which may not be suitable for new types of power systems. For power systems with a high proportion of renewable energy, how to determine the execution price needs to be discussed, as the optimal execution price is related to some random factors and cannot be accurately determined in advance. In the future, reliability options can be combined with revenue estimation methods to explore a reliability option mechanism based on multi-part pricing/revenue estimation methods.

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