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Analysis on the Effect of the Uncertainty of Outside Power on the Equilibrium of Joint Energy and Reserve Market

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Abstract. As a major way to consume new energy, energy transmission across provinces and regions has increased rapidly in recent years. It is of great importance for the construction of the spot market to study the impact of different uncertainty of the outside power on the joint energy and reserve market. Firstly, this paper establishes a joint energy and reserve market equilibrium model that takes into account the uncertainty of the outside power which leads to additional reserve demand. Secondly, a game equilibrium algorithm is proposed to solve the market final equilibrium. The simulation results show that the uncertainty of the outside power will not only reduce market efficiency but also damage the interests of the outside new energy generator itself.

1. Introduction

Cross-provincial energy transmission, as an important way for the absorption of new energy, has developed rapidly in recent years. During the "Thirteenth Five-Year Plan" period, 19 cross-provincial channels will be added and about 70 million kilowatts of new energy and renewable energy will be consumed [1]. In the open electricity market, new energy suppliers as outside units will also participate in market bidding. These participants not only bring lower bidding prices but also bring uncertainty to the grid because of their characteristics. How to conduct bidding research in this electricity market is a problem that must be solved before the mature electricity market is formed.

Many scholars at home and abroad have done in-depth research on the bidding of the electricity market, which can be classified into two ways. One is to provide guidance for the generators to report the optimal bidding strategy by establishing corresponding optimization models [2-3]. The other is to predict the bidding behavior that may appear in the market by solving the market equilibrium [4-6]. Solving the market equilibrium is more complicated than solving the optimal bidding of the power producer. This paper adopts the second way through game theory.

In order to obtain the equilibrium of the energy and reserve market which involves outside new energy suppliers, we consider the impact of the uncertainty of outside power on the system's additional reserve, the reserve income that takes into account both capacity gain and the actual energy gain after being called. Then an equilibrium model of the energy and reserve market that takes into account the total fuel cost of the energy and reserve is established. In the process of solving the equilibrium, the cyclic iterative algorithm based on the game theory method is used to simulate. Lastly, the analysis of the influence of different characteristics of the outside power on the bidding coefficient and the final clearing will be conducted.

2. System model

Day ahead market adopts sealed-bid auction. Market participants report the bidding curve to ISO and ISO minimizes the cost of purchasing electricity and makes the market clear. All rational participants maximize their own profits through strategic quotations.

2.1Local generator characteristics and bidding model

Local generators are supposed to report both the energy and reserve bidding curves in the market. The fuel cost can be described as a quadratic function of the output and the first-order differential is used to obtain the marginal cost. Though the affine processing on the marginal cost, linear supply functions of the power bidding curves are shown as follows. The bidding curve of the reserve market is similar.

$$p(P_{Gi}) = k_{ei}(a_i P_{Gi} + b_i), \forall i \in G_{in} \quad (1)$$

$$p(P_{ri}) = k_{ri}(\alpha_i P_{ri} + \beta_i), \forall i \in G_{in} \quad (2)$$

P_{Gi} is the output of generator i. *p(PGi)* is the power bidding curve of the generator i . *p(Pri)* is the reserve bidding curve of the generator i. a_i、b_i、c_i、α_i、β_i are the sub-factors of fuel cost and the reserve quotation curve respectively. k_{ei}、 k_{ri} are the energy and reserve bidding coefficient of generator i respectively.

2.2Outside generator characteristics and bidding model

Outside power generally include hydropower, thermal power and wind fire bundling. Since it is mainly new energy, there is uncertainty which affects the stability of the local grid and increases the additional reserve demand. Its energy and reserve quotation models are similar to local units as follows:

$$p(P_{Gi})' = k_{ei}'(a_i' P_{Gi}' + b_i'), \forall i \in G_{out} \quad (3)$$

$$p(P_{ri})' = k_{ri}'(\alpha_i' P_{ri}' + \beta_i'), \forall i \in G_{out} \quad (4)$$

2.3Market clearing model of ISO

After receiving the bidding curve from the local and outside generators, the ISO will jointly clear the day ahead market. Taking into account various network constraints, the ISO makes unit commitments to minimize the purchase cost of the energy and reserve. The clearing model is as follows:

$$\begin{aligned} \min f_{ISO} = & \sum_{i\in G}(0.5k_{ei}a_i P_{Gi}^2 + k_{ei}b_i P_{Gi}) \\ & + \sum_{i\in G}(0.5k_{ri}\alpha_i P_{ri}^2 + k_{ri}\beta_i P_{ri}) \end{aligned} \quad (5)$$

$$s.t. \begin{cases} \sum_{i\in G} P_{Gi} - \sum_{k\in L} P_{Dk} = 0 \\ \sum_{i\in G} P_{ri} - r_1 * \sum_{k\in L} P_{Dk} - r_2 * \sum_{i\in G_{out}} P_{Gi} = 0 \\ P_{Gi\min} \le P_{Gi} \le P_{Gi\max}, \forall i \in G \\ P_{ri\min} \le P_{ri} \le P_{ri\max}, \forall i \in G \\ P_{i\min} \le P_{ri} + P_{Gi} \le P_{i\max}, \forall i \in G \end{cases} \quad (6)$$

P_{Dk} is the load demand of the user k. *G* is the set of generators, including outside and local uuncertainty of load. r_2 represents the uncertainty of outside power. $P_{Gi\min}$、$P_{Gi\max}$ are the minimum and maximum power output of generator i respectively . $P_{ri\min}$, $P_{ri\max}$ are the minimum and maximum output of reserve for generator i respectively. $P_{i\min}$, $P_{i\max}$ are the minimum and maximum technical output of generator i respectively.

2.4Two-layer optimization model for generator bidding

After the completion of the market clearing, the ISO returns the winning bid and the clearing price to each participant. For each bidder, they hope to make the most benefits through strategic quotation. Under the premise of the known opponent's bidding strategy, this is actually a two-layer optimization problem. The objective function is to maximize the total profit of the power and the reserve market.

$$\max_{k_{ei},k_{ri}} f_G = \lambda_e P_{Gi} + \lambda_r P_{ri} + \tau\lambda_e P_{ri} - \tau C_i(P_{Gi} + P_{ri}) - (1-\tau) * C_i(P_{Gi}) \quad (7)$$

$$s.t.\begin{cases} k_{ei\min} \le k_{ei} \le k_{ei\max} \\ k_{ri\min} \le k_{ri} \le k_{ri\max} \\ \text{式}(5)\backslash(6) \end{cases} \quad (8)$$

$C_i()$is the fuel cost of generator i. λ_e is the clearing price of electric energy. λ_r is the clearing price of reserve. τ is the reserve rate based on historical data .$k_{ei\min}$, $k_{ei\max}$ are the minimum and maximum of the power quotation coefficient of the generator i respectively .$k_{ri\min}$, $k_{ri\max}$ are the minimum and maximum of the reserve quotation coefficient the generators i respectively.

3. The solution algorithm to the equilibrium

3.1Nash equilibrium

In an n-player game (S, f), S_i is the set of strategies of the player i. S=S1×S2×⋯×Sn is the set of all the players' strategies. f(x)=(f_1(x), ⋯, fn(x)) is the set of the revenue function of all the players under the strategy combination x(x∈S). Each player i chooses a strategy xi which constitutes the strategy combination x=(x1, ⋯, xn) and obtains the revenue f(x). The revenue of each player depends not only on its own strategy but also on the opponent's strategy. xi(xi∈Si) represents the strategy of the i-th player in the strategy combination x and x-i represents the strategy of the opponent. When there is a combination of strategies x*(x*∈S) that all players can't get more benefits by unilaterally changing their own strategies, this strategy combination x* is the Nash equilibrium of the game, which is:

$$\forall i, x_i \in S_i : f_i(x_i^*, x_{-i}^*) \ge f_i(x_i, x_{-i}^*) \quad (9)$$

The solution of the equations as shown in Equation 10 is the Nash equilibrium, which is the main method used to solve the market equilibrium. There are two ways to solve the root of the equations. One is to use the Newton method such as the nonlinear complementarity algorithm, and another is the Gaussian iterative iteration such as the cyclic iterative algorithm.

$$\begin{cases} x_1 = f_1(x_2, \cdots x_k \cdots, x_n), k \ne 1 \\ x_2 = f_2(x_1, \cdots x_k \cdots, x_n), k \ne 2 \\ \cdots \\ x_n = f_n(x_1, \cdots x_k \cdots, x_{n-1}), k \ne n \end{cases} \Rightarrow (x_1^*, x_2^* \cdots, x_n^*) \quad (10)$$

3.2Procedures of the cyclic iterative algorithm

This paper uses the cyclic iterative algorithm. It first transfers each equation into the optimal response function. Then randomly generates an initial value of the solution and it iterates according to the optimal response function. Finally the algorithm approaches the solution of the equations. The specific steps of the cyclic iterative algorithm are as follows:

(1) Define the rules for bidding in the electricity market such as the number of bidding participants n, the strategies choices of each participant Sk(k=1,2⋯n) and the set of strategies {S1, S2 ,...,Sn} for all participants;

(2) Initialization when t=0. For the initial strategy of each participant, we randomly generate a strategy within the strategy set {S1(t), S2(t),...,Sn(t)};

(3) Solve the two-layer optimization model of the bidding participant i in turn and obtain the next round of strategies;

$$S_i(t+1) = f_i\left(S_2(t), \cdots S_k(t) \cdots, S_n(t)\right) \quad k \ne i \quad (11)$$

Sk(t) is the strategy of the participant k in the t-th iteration.

(4) Algorithm termination condition: Whether the revenue convergence of the participant is met?

(5) If not, then t=t+1, return to step (3). If it is satisfied, then the final strategy combination is the Nash equilibrium solution.

4. Case study

When the outside power is thermal power or hydropower, there will be no uncertainty of output. However, if it is formed of wind and fire power, the higher the proportion of wind power, the greater the uncertainty of its output and the higher additional reserve ratio. Different characteristics of outside power will cause different ratio of reserve, resulting in different market bidding.

4.1Data

Cases are based on an IEEE standard 3-node test system. The 3-node test system consists of one outside unit and four local units. The network topology is shown in Figure 1. The outside unit G1 is linked to node 1 and the local generators G2~5 are linked to node 2. The load is at node 3. All the simulations are performed on the MATLAB. In this case, the probability for calling reserve is 50% and the load demand is 80,000 MW. The total demand for reserve is 10% of the load plus 10% of the outside bidding power.

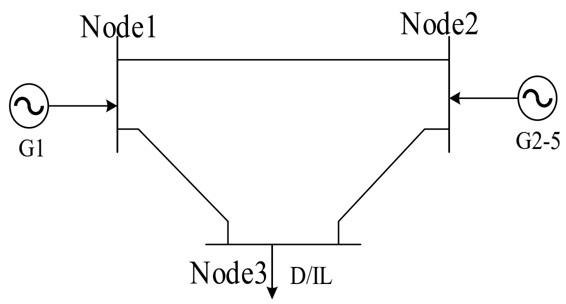

Fig.1 Topology of Standard three node network

4.2Effect of different characteristics of outside power on energy and reserve bidding coefficient

The energy bidding coefficient of the generators under different characteristics of the outside power is shown in Table 1. It can be seen from the table that the energy quotation coefficient of the local unit (G2~5) increases with the rising of the uncertainty of the outside power, while that of the outside unit (G1) decreases with the rising of the uncertainty. As the uncertainty increases, the additional reserve capacity of the system caused by outside units will increase too. After weighing the profits, the ISO will inevitably reduce the purchase of power from outside units, which directly causes the profit of outside units to decrease. To compensate for the reduction in the bids caused by the increasing uncertainty, outside generators are pushed to quote a lower price. While for local units, as the uncertainty increases, the ISO will reduce the purchase from outside units and instead purchase more from local units. The market supply remains unchanged but the demand increases. Local generators will inevitably quote a higher price to make more profits. The variation tendency of the reserve quotation coefficient under different characteristics of the outside power is consistent with that of energy. Since the supply and demand ratio in the reserve market is relatively small and the compensation standard for the reserve is relatively high, generators quote the prices at the minimum bidding level, which is close to full competition.

Tab.1 Bidding strategies under different outside power characteristics

characteristic	The energy bidding coefficient					The reserve bidding coefficient				
	G1	G2	G3	G4	G5	G1	G2	G3	G4	G5
Outside 0%	1.0480	1.0485	1.0419	1.0414	1.0430	0.5	0.5	0.5	0.5	0.5
Outside 10%	1.0087	1.0528	1.0456	1.0467	1.0460	0.5	0.5	0.5	0.5	0.5

4.3Effect of different characteristics of outside power on equilibrium

The results of equilibrium are shown in *T*able 2. Table 2indicates that when there is no uncertainty in outside power, the outside unit, as the lowest-priced generator, has a competitive advantage in the energy market and acts as a marginal unit. However, when the certainty increases the competitive advantage is inconspicuous because of the additional reserve demand. In order to cope with the reduction of the winning bid in the energy market, the quotation coefficient has to be reduced. At this time, the local units act as marginal units which determine the market clearing price. As the ISO purchases more energy from the local units, the market supply-demand ratio decreases and the local units inevitably raise the bidding price, resulting in a higher clearing price. The increase in the uncertainty of the outside power also leads to an increase in the total reserve demand, which leads to an increase in the reserve clearing price.

Tab.2 Equilibrium clearing results under different outside power characteristics

characteristic	Marginal price of the units in the energy market					Marginal price of the units in the reserve market				
	G1	G2	G3	G4	G5	G1	G2	G3	G4	G5
Outside 0%	239.997	239.997	239.997	239.997	239.997	75.994	75.994	75.994	75.994	75.994
Outside 10%	232.524	240.522	240.522	240.522	240.522	79.989	79.989	79.989	79.989	79.989

The main problem of current wind power consumption is the additional reserve cost caused by its uncertainty and reverse peak regulation. The reduction of uncertainty can promote the consumption of wind power. From the perspective of the electricity market, reducing the uncertainty of wind power output will help to increase the winning bids and reduce the clearing price of the electricity market. It is recommended that the wind generators purchase demand response from the user side or develop an accurate wind forecasting system to improve the efficiency of the market.

5. Conclusion

This paper establishes an equilibrium model of joint energy and reserve markets under the consideration of outside power formed of new energy sources. The 3-node test system is used to simulate the equilibrium using the cyclic iterative algorithm and the equilibrium results under different characteristics of the outside power are simulated. The potential relationship between the bidding strategies and the characteristics of the outside power is analyzed. Research indicates:

1) The greater the uncertainty of the outside power, the lower the quotation coefficient for outside units and the higher the quotation coefficient for the local units, resulting in the higher clearing price. Thus reducing the uncertainty of outside power is conducive to improving market efficiency.

2) With the advent of uncertainty, the outside units will switch from the marginal unit to the non-marginal unit. Thus reducing the uncertainty of outside power is beneficial to increase its own revenue.

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