Equilibrium Model of Electricity Market Bidding Considering Incentive-based Demand Response

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Abstract. In the initial stage of electricity market construction, incentive-based demand response can effectively mitigate price spikes. Considering the overall equilibria of the market, it is of great significance to study the impact of incentive-based demand response on market clearing and participants’ behaviours. Firstly, this paper analyzes the compensation methods of incentive-based demand response and establishes an equilibrium model of day-ahead electricity market bidding that takes into account demand response. Secondly, considering the overall equilibrium conditions of the market, the overall equilibrium model of the market is established. Results show that the incentive-based demand response mechanism has a restraining effect on the generators’ bidding, and the load reduction effect is prominent when the network is congested.

1. Introduction

For a period of time, the monopoly and integration mode of the power industry is gradually being broken and turns to marketization. In the initial stage of electricity market construction, due to the low participation of the load side in the market, liberalization of the market competition is limited. At this stage, the participation of demand response (DR) resources can better adjust market prices and improve the ability to cope with system’s uncertainty.

DR mechanisms are mainly divided into two categories, price-based demand response (PDR) and incentive-based demand response (IDR)[1-3]. Price-based demand response refers to the adjustment of electricity demand stimulated by price signals. Incentive-based demand response means that users obtain a certain amount of compensation by actively reducing their own power demand when the power system supply or demand are tight. However, many current studies focused on the impact of demand response on the power generation side, ignoring the overall market equilibrium with competitive generators and demand.

In order to study the influence of IDR on power generation bidding under market equilibrium, this paper analyzes the compensation method of IDR from the inhibitory effect of IDR on market clearing prices. Based on the incentive-based price curve set by the market, compensation for load curtailment is added to the user side. Then, with the goal of maximizing the revenue of generators, a day-ahead market generator bidding equilibrium model that takes into account demand response is established to solve the strategies selection and optimization problems of generators. This paper also considers the
overall equilibrium conditions of the market to establish an overall market equilibrium model. Lastly, the inhibitory effect of IDR resources on generators bidding is simulated under different incentive coefficients and network congestion.

2. Compensation method of incentive-based demand response
The development of a sound power market needs to rely on enhancing the price elasticity on the load side. However, it is more difficult to implement bilateral bidding for both power generation and load in the short-term market construction. In order to ensure healthy competition in the market, this paper introduces an incentive mechanism on the load side as a transitional plan, and adopts the load curtailment method of IDR when electricity prices are spikes to stabilize market clearing prices. The advantage of this mechanism is that it not only provides operational convenience for market operators, but also plays a role in linking up with the user side bidding mechanism in the mature stage of the electricity market. In a mature power market, the market adopt a bidding model, with the load side participating in the bidding, and the load side report the corresponding load curve that represent the acceptable market price under different demands to ISO. Therefore, this paper considers a certain multiple of the load reduction compensation price curve as price compensation for demand response resources.

With this compensation mechanism, the load side has the driving force for load reduction, and the market will compensate users who provide load reduction services at the new clearing price. Users who have not participated in load curtailment are the direct beneficiaries of load curtailment, so the compensation cost is borne by them. The final electricity price of users is the clearing price after load curtailment plus the apportioned demand response compensation cost. The actual electricity price for these users is the clearing price after load curtailment plus the apportioned demand response compensation cost.

Figure 1. Bidding equilibrium model of generator considering IDR.
3. Bidding Equilibrium Model of Generator under Incentive-based Demand Response

The bidding equilibrium model considering the IDR is composed of two modules that are the equilibrium model of individual generators bidding in the day-ahead market and the equilibrium model of the overall market [4-5]. The overall structure of model is illustrated in figure 1.

3.1. Bidding equilibrium model of generators

When the day-ahead market clears, the game between maximizing the profits of generators and minimizing costs of market operators is a bi-level optimization model. The lower level is a clearing model that minimizes electricity purchasing cost. The upper level is the optimization model of generators bidding strategy considering profit maximization. In this paper, the bidding model and profit model of generators adopt the form of literature [5].

3.2. Incentive-based demand response price compensation model

Assuming that the loss of load curtailment users is covered by the compensation mechanism, the compensation price curve on the load side is formulated based on the principle that the greater the load curtailment and the higher the compensation price. The relationship between compensation price and load curtailment as follows:

\[ P_{\text{comp}}(\Delta Q_i) = k_{\text{cut}}(m\Delta Q_i + n) \]  

When the system load is actively curtailed, the total compensation price is the integral of the compensation price to the curtailment amount.

\[ o(\Delta Q) = \int P_{\text{comp}} d\Delta Q_i = \int k_{\text{cut}}(m\Delta Q_i + n)d\Delta Q_i = k_{\text{cut}}\left(\frac{1}{2}m\Delta Q_i^2 + n\Delta Q_i\right) \]

Where \( P_{\text{comp}}(\Delta Q_i) \) is price compensation curve for load curtailment. \( k_{\text{cut}} \) is uniform load curtailment incentive coefficient in the market. \( m, n \) are the first-order coefficient and constant term of the load incentive curve. \( o(\Delta Q_i) \) is compensation amount corresponding to load reduction \( \Delta Q_i \).

3.3. Market clearing model of ISO

Due to the demand response on the load side, the ISO's market clearing goal is to minimize the sum of power generation costs and compensation costs. Taking into account various network constraints and load curtailment constraint, this paper uses the clearing method of DC optimal power flow. The clearing model is as follows:

\[ \begin{align*}
\min f_{\text{ISO}} &= \sum_{i \in \text{Gen}} k_{\text{cut}}(0.5a_i P_{\text{Gi}}^2 + b_i P_{\text{Gi}}) + \sum_{j \in \text{load}} k_{\text{cut}}(0.5m\Delta Q_i + n\Delta Q_i) \\
\text{s.t.} \quad &\sum_{j \in \text{cu}} P_{\text{Gi}} - (\sum_{j \in \text{cu}} P_{\text{Dj}} - \sum_{j \in \text{cu}} \Delta Q_j) - \sum_{y} B_{uy} \theta_y = 0, \forall u \in \text{bus} \\
&-S_y \leq B_{y} (\theta_j - \theta_i) \leq S_y, \forall ij \in \text{branch} \\
&P_{\text{Gi,min}} \leq P_{\text{Gi}} \leq P_{\text{Gi,max}}, \forall i \in \text{Gen} \\
&0 \leq \Delta Q_j \leq P_{\text{Dj}}, \forall j \in \text{load}
\end{align*} \]

Where \( \text{bus} \) is the set of buses in the network. \( \text{branch} \) is the set of transmission line. \( \text{Gen} \) is the set of generators. \( \text{load} \) is the set of load. \( \theta \) is node phase angle. \( P_{\text{Dj}} \) is the initial load demand of the user \( j \). \( \Delta Q_j \) is load curtailment of the user \( j \). \( B_{uy} \) is the network admittance matrix. \( S_y \) is the maximum transmission line capacity limit. \( P_{\text{Gi,min}}, P_{\text{Gi,max}} \) are the unit active power output limits.

3.4. Market overall equilibrium model

According to game theory, the condition for the market to reach equilibrium is all power generators participating in market competition cannot increase revenue through changes in their bidding strategies.
If (5) is satisfied, the strategy set of each generator is considered to be the optimal strategy when the market is in equilibrium.

\[ R_i(k^*_i, k^*_j) \geq R_i(k_i, k^*_j) \quad \forall i \in \text{Gen}, k_i \in S_i \]  

(5)

Where \( S_i = \{k_1, k_2, k_3, \ldots, k_n\} \) is the set of strategies of the player \( i \). \( R_i(k^*_i, k^*_j) \) represents the revenue that the generator \( i \) can obtain when choosing the individual optimal strategy \( k^*_i \), given the set of opponent strategies \( k^*_j \). \( k_i \) is the strategy selected by generator \( i \). The bidding strategy selected by the generators is based on the profit of ISO after the market clearing. Therefore, the return result \( R_i(k^*_i, k^*_j) \) corresponding to the individual optimal strategy is the maximum return when the current opponent's strategy combination is determined. Only when the strategy \( k_i \) is individual optimal, the equal sign of (5) holds.

(5) is processed as:

\[ R_i(k^*_i, k^*_j) \leq \max R_i(k_i, k^*_j) \quad \forall i \in \text{Gen}, k_i \in S_i \]  

(6)

The equal sign holds when the strategy selected on the left side of the inequality is the optimal solution given the opponent strategy. The fitness function is given:

\[ \text{fitness}(k^*_i, k^*_j) = \frac{R_i(k^*_i, k^*_j)}{\max R_i(k_i, k^*_j)} \quad \forall i \in \text{Gen}, k^*_i \in S_i \]  

(7)

The objective function to achieve market equilibrium is:

\[ \max \text{fitness}(k^*_i, k^*_j) = \max \sum_{i \in \text{Gen}} \frac{R_i(k^*_i, k^*_j)}{\max R_i(k_i, k^*_j)} \quad \forall k^*_i \in S_i \]  

(8)

4. Case study
The case considers the influence of load-side incentives on generators bidding from the load-side incentive coefficient and network congestion. A combination of particle swarm and interior point method is used to solve the optimal solution of the bi-level optimization model[5-6]. Cases are based on an IEEE standard 3-node test system. The network topology is shown in figure 2. The outside unit G1~3 are linked to node 1~3. In this case, generator bidding coefficient \( k_i \in [1, 2], m = 0.01, n = 24 \). The load demand of L1~3 are 200MW, 350MW and 350MW respectively.

![Figure 2. Topology of standard three node network.](image)

4.1. Simulation considering different load incentive coefficients
Assuming that the overall supply-demand ratio of the market remains unchanged, adjust the load curtailment incentive coefficient \( k_{\text{cur}} \) to observe its inhibitory effect on bidding. In order to compare the impact of the incentive load curtailment mechanism on the bidding, Table 1 gives the market clearing results without considering the load curtailment, and then changes \( k_{\text{cur}} \) on the load side for simulation.
Compared with the case where the system has not been curtailed, the bidding strategy coefficient of generator is generally reduced under different curtailment coefficients. When the compensation cost required for demand response is lower, the demand response resources of system dispatch will increase, and generators tend to lower their strategy coefficients. However, a high compensation incentive coefficient will excessively compensate users, resulting in demand-side resources not being scheduled.

### Table 1. Market clearing results under different compensation coefficients $k_{\text{cut}}$.

| The compensation incentive coefficient | The bidding coefficient of generator | LMP(¥/MW) | Load curtailment(MW) |
|---------------------------------------|-------------------------------------|-----------|----------------------|
|                                       | G1       | G2       | G3       | U1     | U2     | U3     |
| -                                     | 2.00    | 1.00    | 1.00    | 40.40  | -      | -      |
| 1                                     | 1.00    | 1.00    | 1.00    | 22.32  | 0.02   | 0.00   | 200.00 |
| 1.1                                   | 1.31    | 1.00    | 1.00    | 26.40  | 2.01   | 2.82   | 3.52   |
| 1.2                                   | 1.43    | 1.00    | 1.03    | 28.80  | 0.02   | 0.01   | 0.01   |
| 1.3                                   | 1.00    | 1.00    | 1.50    | 31.19  | 0.01   | 0.01   | 0.01   |

4.2. **Simulation considering transmission congestion**

Set the transmission constraints between node 1 and node 2 as $L_{1-2}^{\text{max}} = 50\text{MW}$. Table 2 gives the market clearing results considering the load curtailment and transmission congestion.

### Table 2. Market clearing results considering transmission congestion.

| The compensation incentive coefficient | The bidding coefficient of generator | LMP(¥/MW) | Load curtailment(MW) |
|---------------------------------------|-------------------------------------|-----------|----------------------|
|                                       | G1       | G2       | G3       | G1     | G2     | G3     | U1     | U2     | U3     |
| -                                     | 2.00    | 2.00    | 1.34    | 41.50  | 47.50  | 44.50  | -      | -      | -      |
| 1                                     | 1.15    | 1.23    | 1.00    | 25.48  | 29.68  | 27.34  | 88.63  | 100.35 | 50.44  |
| 1.1                                   | 1.27    | 1.32    | 1.04    | 28.73  | 33.70  | 31.22  | 28.00  | 55.71  | 31.01  |
| 1.2                                   | 1.38    | 1.42    | 1.39    | 29.63  | 34.44  | 32.03  | 2.77   | 12.57  | 4.56   |
| 1.3                                   | 1.50    | 1.63    | 1.56    | 31.93  | 39.49  | 25.76  | 3.25   | 7.25   | 3.33   |

In the case of transmission constraints, the price of blocked nodes (e.g. node 2) will increase significantly. Through demand response, especially the response resources of congested nodes, it will have a better effect on hold down locational marginal price. Similar to the case where there is no congestion, as the curtailment compensation coefficient decreases, the restraining effect of response resources on the bidding of generators becomes more obvious. In short, the final equilibrium bidding shows a downward trend as the curtailment compensation coefficient decreases.

5. **Conclusion**

This paper establishes a bidding equilibrium model of power producers considering IDR and overall market equilibrium conditions. The IEEE standard 3-node test system is used to simulate the equilibrium under different incentive coefficient and network congestion situations. The main conclusions of this paper are as follows:

1) Through the participation of incentive-based load response resources, the excessively high bidding of generators is suppressed, which reduces the overall cost of the system to a certain extent.

2) Regardless of transmission congestion, a smaller load-side incentive coefficient is conducive to encouraging users to participate in demand response, and restraining the bidding on the generation side more explicitly.
3) Considering the network transmission congestion, the scheduling of load curtailment resources increases significantly. ISO will give priority to the resources that are most effective for congestion mitigation, so the load curtailment at the congestion node is dispatched more.

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