Research on the impact of demand response programs in day ahead market on the oligarchs in the electricity market

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Abstract. In order to study the influence of different types of demand response on the members of the electricity market in the market, a multi-agent model is used to study the behavioral strategies of independent market oligarchs in the electricity market in the day-ahead market, and the security-constrained unit commitment model is used to simulate specific market transactions. First, a demand response model was established, and the relationship between consumer profit and cost was determined using Taylor series expansion. Then the characteristics of the oligopoly market were analyzed, and a market clearing model by using a commitment model of security-constrained units was established, with the objective of maximizing agency profit, and including operation constraints. Finally, the IEEE6 node system was used for simulation to analyze the influence of different types of demand response behaviors on oligarchs and demonstrate the effectiveness of the model.

1. Introduction

The development of information and communication technology and worries about environmental energy make demand response (DR) one of the ways to solve the contradiction between power supply and demand. DR is directly related to the power market with high reliability and efficiency, and is also an important part of the construction of smart grid [1]. From the perspective of power system, consumers participating in demand response can obtain profits, which also affects the strategies of power producers, especially in the oligopoly environment [2].

Among the demand response projects, emergency demand response program (edrp) and interruptible/reducible services are more closely related to the unit commitment problem, and thus more related to the strategies of power generators. The traditional price based demand response mainly includes tou, CPP and RTP [3]. In the day ahead market, generators and users quote one day in advance, while the type of demand response project affects the type, mode and quantity of transactions between the two sides.

At present, the research on the impact of demand response on power market mainly focuses on market mode and control mode. Literature [4] describes the role of demand response in the power market. Literature [5] analyzes the impact of demand response mechanism on power market and users. Literature [6] analyzes the equilibrium problem of oligopoly electricity market after the implementation of emission trading. Literature [7] analyzes oligopoly competition in the electricity market based on load...
forecasting. It can be seen that the above documents rarely analyze the influence of demand response on oligarch behavior in the electricity market from the previous day.

Different from the above literature research, this paper studies the influence of demand response items on oligarchs' trading behavior in the electricity market, and simulates the specific market transactions by using the safety constraint unit combination problem. First, a demand response model is established, and Taylor series expansion is used to determine the relationship between consumer profit and cost. Then, the characteristics of oligarch market are analyzed, and the market clearing model is established by using the safety constrained unit commitment model, which takes the maximum profit of agent as the goal and considers the operation constraints. Finally, IEEE6 node system is used to simulate the impact of different types of demand response behavior on oligarchs.

2. Demand Response Model

The demand response model can reflect the user's sensitivity to electricity price changes in different periods. Users can adjust their electricity consumption behavior through the demand response principle. Electricity price changes, incentive measures and punishment measures can reduce users' electricity consumption during peak power consumption periods or when the system is threatened. Demand response is mainly divided into two categories: price based demand response and incentive based demand response.

Assuming that the consumer's initial power demand is \( P_{dt}^0 \) and the adjusted power demand at time \( t \) is \( P_{dt} \), considering the influence of electricity price change or incentive policy, the influence of demand response on consumer's power consumption is as follows:

\[
\Delta P_{dt} = P_{dt}^0 - P_{dt}
\]

The level \( \zeta_t \) of excitation can be expressed as:

\[
\zeta_t = \Sigma_t \cdot \Delta P_{dt}
\]

Similarly, the level of punishment \( \xi_t \) can be expressed as:

\[
\xi_t = \Pi_t \cdot \left( P_{dt}^{cap} - \Delta P_{dt} \right)
\]

The profit \( \beta_t \) of the user at time \( t \) can be expressed as:

\[
\beta_t = \rho_t - P_{dt} \lambda_t + \zeta_t - \xi_t
\]

Where \( \rho_t \) is the total revenue of the user at time \( t \) and is a function of \( P_{dt} \).

In order to optimize the profits of users in demand response projects, the following formula is derived:

\[
\frac{\partial \beta}{\partial P_{dt}} = \frac{\partial \rho}{\partial P_{dt}} - \lambda_t + \frac{\partial \zeta}{\partial P_{dt}} - \frac{\partial \xi}{\partial P_{dt}} = 0
\]
Considering that the profit of general users is quadratic function, the user profit function is expanded by Taylor series as follows:

$$\rho_t = \rho_t^0 + \frac{\partial \rho}{\partial P_{dt}} \Delta P_{dt} + \frac{\partial^2 \rho}{2 \partial (P_{dt})^2} (\Delta P_{dt})^2$$ (6)

Users have a certain degree of flexibility for electricity prices, which will be taken into account, and users' income will become:

$$\rho_t = \rho_t^0 + \lambda_t^0 \cdot \Delta P_{dt} \cdot \left(1 + \frac{\Delta P_{dt}}{2E_i P_{dt}^0}\right)$$ (7)

Where $E_i$ is the user's self-elasticity to the electricity price, and the above formula is brought into (6) to obtain:

$$P_{dt} = P_{dt}^0 + E_i \frac{P_{dt}^0}{\lambda_t^0} \left(\lambda_t^0 - \lambda_t^0 + \zeta_t - \xi_t\right)$$ (8)

Carry out multi-period expansion on the above formula to obtain a demand response model:

$$P_{dt} = P_{dt}^0 + E_i \frac{P_{dt}^0}{\lambda_t^0} \left(\lambda_t^0 - \lambda_t^0 + \zeta_t - \xi_t\right)$$

$$+ \sum_{t'=1, t' \neq t}^T \left[ E_{t,t'} \frac{P_{dt}^0}{\lambda_{t'}^0} \left(\lambda_{t'}^0 - \lambda_{t'}^0 + \zeta_{t'} - \xi_{t'}\right) \right]$$ (9)

Where $E_{t,t'}$ is the mutual elasticity of users to electricity prices. The formula reflects the optimal power demand from the user's perspective.

3. Electricity Market Model

3.1. Brief introduction of power market

Electricity market is also a kind of market form. According to the degree of market competition, there are mainly complete competition market, monopoly competition market, oligopoly market and complete monopoly market. The characteristics of each market model are shown in Table 1.
### Table 1. Classification of electricity markets

| Market type           | Number of firms | Degree of product difference | Degree of price control | Ease of access | Market examples          |
|-----------------------|-----------------|------------------------------|-------------------------|----------------|--------------------------|
| Perfect competition   | Quite a lot     | No difference at all         | No                      | Very easy      | Some agricultural products |
| Monopolistic competition | Quite a lot     | Have difference             | Somewhat                | Relatively easy | Cigarettes, candy         |
| Oligopoly             | Several         | Not necessarily              | To a considerable extent | Relatively difficult | Steel, cars               |
| Complete monopoly     | One             | Only                         | To a great extent       | Very difficult | Public utilities          |

Microeconomics theory points out that a perfectly competitive market can be regarded as a model to minimize costs or maximize profits. Therefore, for a completely competitive electricity market, the best form is to describe it with an optimization model. For complete monopoly, it can be simulated as the problem of profit maximization of monopolists. In this model, electricity price comes from demand function. In incomplete competition, monopoly competition, we need to solve the problem of profit maximization for each participant at the same time. In addition, the model of oligopoly will change with time.

### 3.2. Model of oligopoly power market

This paper uses agent system to model the electricity market. Based on this, every power market participant pursues maximum profit as an agent. Therefore, the node price of energy market is used to determine the optimal strategy behavior in power generation. The demand-side behavior uses the demand response model in the previous section. In addition, the independent system operator (ISO) uses the safety constrained unit commitment model to clear the day ahead electricity market, and seeks the maximization of social welfare under the consideration of safety constraints. The model proposed in this paper is shown in the figure below.

![Figure 1. Illustration of proposed model](image-url)

Each agent optimizes its own profit, mainly referring to the strategy within the next trading day. The strategic model of each generator is as follows:
\[ f = \max \sum_{t=1}^{T} \left\{ P_{i,t} \lambda_t - a_i P_{i,t}^2 - b_i P_{i,t} - c_i u_{i,t} \right\} - S_{U_i} y_{i,t} - S_{D_i} z_{i,t} \] \hspace{1cm} (10)

Among them, \( P_{i,t} \) and \( T \) are the output of unit I during T period; \( \lambda_t \) is the electricity price in t period; \( a_i, b_i, c_i \) are cost coefficients; \( u_{i,t} \) is the start-stop status of unit i during t period; \( S_{U_i} \) and \( S_{D_i} \) are the start-up cost and rotary standby of the unit; \( y_{i,t} \) and \( z_{i,t} \) are auxiliary binary variables for unit combination respectively.

\[ u_{i,t} - u_{i,t-1} = y_{i,t} - z_{i,t} \hspace{1cm} (11) \]

\[ y_{i,t} + z_{i,t} \leq 1 \hspace{1cm} (12) \]

The objective function of this model is that the generators participating in the market before the day have the largest income. Consider using quadratic function to simulate the cost of the generator, and also taking into account the start-up and shutdown costs of the unit.

The constraints are as follows:

(1) Unit output constraints

\[ P_{i}^{\min} u_{i,t} \leq P_{i,t} \leq P_{i}^{\max} u_{i,t} \hspace{1cm} (13) \]

Among them, \( P_{i}^{\min} \) and \( P_{i}^{\max} \) are the lower limit and upper limit of unit i respectively.

(2) Unit climbing constraints

\[ P_{i,t} - P_{i,t-1} \leq R_{U_i} \left( 1 - y_{i,t} \right) + y_{i,t} P_{i}^{\min} \hspace{1cm} (14) \]

\[ P_{i,t} - P_{i,t-1} \leq R_{D_i} \left( 1 - z_{i,t} \right) + z_{i,t} P_{i}^{\min} \hspace{1cm} (15) \]

Among them, \( R_{U_i} \) is the climbing rate of unit i; \( R_{D_i} \) is the climbing rate of unit i.

(3) Start and stop time constraints

\[ y_{i,t} + \sum_{j=1}^{M_{U_i}} z_{i,t+j} \leq 1 \hspace{1cm} (16) \]

\[ z_{i,t} + \sum_{j=1}^{M_{D_i}} y_{i,t+j} \leq 1 \hspace{1cm} (17) \]

Among them, \( M_{U_i} \) is the minimum climbing time for unit i; \( M_{D_i} \) is the minimum climbing time for unit i.
In order to simulate the effect of ISO, the problem of safety constrained unit commitment is solved, and the best strategy for power producers to participate in the day-to-day market is obtained. The optimal solution includes the unit combination state and generation output of the power producer and the quotation of the next trading day. Therefore, the objective function of maximizing social welfare is as follows:

$$f = \max \sum_{t=1}^{T} \left( \sum_{c=1}^{N_c} P_{dc,t} \lambda_t - \sum_{i=1}^{N_i} P_{i,t} \lambda_t \right)$$

(18)

Among them:

$$\sum_{i=1}^{N_i} P_{i,t}^{\text{max}} \ u_{i,t} \geq \sum_{c=1}^{N_c} P_{dc,t} + SR_t$$

(19)

Among them, $N_c$ is the number of demand response users; $SR_t$ is the rotation reserve at time $t$.

The restriction of AC power flow has great influence on power market transactions. In order to improve the speed of power flow calculation, the nonlinear/linear AC power flow model is considered in this paper. Based on this algorithm, the nonlinear AC power flow under normal conditions is solved, and then the convergence check is carried out by using the linearized Jacobian matrix [8].

4. Case Study

4.1. System description

In this paper, IEEE6 node system is selected for simulation [9]. In the actual electricity market, most regulators can't accurately know the cost function of market participants, only can make corresponding estimates. Considering different price policies, this paper chooses different time-sharing price and three kinds of peak price. It is assumed that 20% of users can participate in demand response load. See tables 2 and 3 below for specific data, where the base scenario refers to fixed tariff. In the base case, the market average price is the average of the sum of the prices in all periods. In the projects of TOU price and peak price, the average price is the average price in valley period. It can be seen that there are three tariff levels for tou1 and tou2, and four tariff levels for tou3. The price of emergency demand response is the same as that of the basic case. In this paper, 30% of the price is considered as the incentive, and the user's self-elasticity and mutual elasticity are referred to [10].

| Scene                    | Valley period (1-8) | Normal period (9-11, 22-24) | Peak period (12-14, 19-21) | Most peak period (15-18) |
|-------------------------|---------------------|-----------------------------|---------------------------|-------------------------|
| Basic scenario          | 63.2                | 63.2                        | 63.2                      | 63.2                    |
| TOU-1                   | 31.6                | 63.2                        | 94.8                      | 94.8                    |
| TOU-2                   | 15.8                | 63.2                        | 126.4                     | 126.4                   |
| TOU-3                   | 31.6                | 63.2                        | 94.8                      | 189.6                   |
| CPP-1                   | 63.2                | 63.2                        | 126.4                     | 126.4                   |
| CPP-2                   | 63.2                | 63.2                        | 252.7                     | 252.7                   |
| EDRP                    | 63.2                | 63.2                        | 63.2                      | 63.2                    |
Table 3. Real time prices ($/MWh)

| Period of time | Price | Period of time | Price |
|----------------|-------|----------------|-------|
| 1              | 54.7  | 13             | 67.9  |
| 2              | 52.8  | 14             | 69.2  |
| 3              | 51.2  | 15             | 74.7  |
| 4              | 50.1  | 16             | 82.1  |
| 5              | 50.2  | 17             | 82.4  |
| 6              | 51.7  | 18             | 72.5  |
| 7              | 54.4  | 19             | 71.6  |
| 8              | 57.7  | 20             | 66.9  |
| 9              | 60.7  | 21             | 66.9  |
| 10             | 63    | 22             | 64.9  |
| 11             | 65.2  | 23             | 59.8  |
| 12             | 66.7  | 24             | 59    |

4.2. Example analysis

Figure 2 below shows the implementation effect of different demand response items under different quotations by generator 1. It can be seen that different requirements and corresponding items make the price quoted by Generator 1 in the market a few days ago different. Based on this, the price quoted by generator 1 in peak price 1 project is lower than that of other projects at peak load time. The main reason is that the demand is lower during this period after the demand response project. In order to illustrate the behavior of other market participants, consider the price of generator 2 under two peak prices, as shown in Figure 3. It can be seen that by increasing the peak price of electricity, the load of electricity is reduced, and the power producer 2 also reduces its offer so as to be able to win the bidding in the peak period.

Figure 2. Impact of different DRPs on the offers of generator

Figure 3. Impact of different types of CPP program on the offers of generators
This paper compares the influence of different types of TOU price on the output of generator 1. According to Figure 4, the output of generator 1 is affected by the time-of-use electricity price. The output increases during the electricity price valley period and decreases during the peak period.

![Figure 4](image1.png)

**Figure 4.** Impact of different types of TOU program on the offers of generators

Figure 5 shows the influence of TOU price on the electricity market price during peak hours, when the quotation of the system generator is reduced. It can be seen that time-of-use electricity price can weaken the market power of power producers during peak hours when power producers become oligarchs. Table 4 shows the effect of demand response on Lerner index. Through the comparison with the basic scenario, we can find that demand response projects can reduce part of market power and improve market efficiency. Among the demand response projects, the high peak price projects have the most obvious effect on the weakening of market power. The third time-sharing price and the first peak price are also more effective in this paper.

![Figure 5](image2.png)

**Figure 5.** Impact of different types of TOU program on the market clearing price

| Scenario | Lerner index |
|----------|--------------|
|          | Generator 1  | Generator 2 | Generator 3 |
| Basic scenario | 0.72 | 0.33 | 0.61 |
| TOU-1 | 0.70 | 0.31 | 0.62 |
| TOU-2 | 0.69 | 0.31 | 0.62 |
| TOU-3 | 0.69 | 0.30 | 0.62 |
| CPP-1 | 0.70 | 0.30 | 0.61 |
| CPP-2 | 0.63 | 0.11 | 0.51 |
| EDRP | 0.71 | 0.32 | 0.63 |

**Table 4.** Market power indices for different DRPs
5. Summary
This paper studies the influence of different types of demand responses on the behavior of oligarchs in the electricity market. The game theory is used to consider the interaction of market competitors and the market transactions that are influenced by the safety constraint of unit combination. Through simulation analysis, different demand response items have different impacts on the strategy of the power market oligarchs. Using price based demand response can reduce the quoted price of the power producer according to the peak price and weaken its market power. Because only the cost function of quadratic function is considered in this paper, the coefficient of cost function among competitors will change greatly, so in the next stage, stochastic programming is considered.

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