Research on Demand Response Aggregators Participating in Power Market Based on Bi-level Optimization

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Abstract. With the rapid development of smart grid technology, how demand side resources participate in power market has become a research hotspot. This paper proposes a bi-level optimization model for demand side resource aggregators to participate in electricity market transactions. In the bi-level model, the lower level is the wholesale market clearing model aiming at the maximum social benefit, and the upper level is the bidding decision model aiming at the maximum power consumption benefit of air conditioning load. The case study demonstrates the feasibility and effectiveness of the model.

Keywords: demand side resource; power market; bi-level optimization; bidding strategy.

1. Introduction
With the rapid development of smart grid technology, how demand side resources participate in power market bidding has become a research hotspot. There are three kinds of transaction modes in foreign mature wholesale markets: power pool mode, bilateral transaction mode and "pool + bilateral transaction" mode. Among them, the mode of "pool + bilateral transaction" allows users and generators to bid at the same time, which can promote the complete open competition of power market. Demand side resources can directly participate in market bidding as large users, or select demand side resource aggregators to participate in market bidding, which can effectively use demand side resources to provide services for power system. In this paper, the reference price effect [1-2] of behavioral economics is introduced to describe the user's electricity consumption behavior, and a bi-level optimization model of demand side resource aggregators participating in electricity wholesale market bidding is constructed. The lower level is the clearing model of wholesale market, and the upper level is the quotation model of demand side resource aggregators. The decision results of the upper layer will affect the objectives and constraints of the lower layer, and the lower layer will feed back the decision results to the upper layer to realize the interaction of the upper and lower layers. The two-layer decision model reflects the idea of hierarchical and partitioned dispatching of power system.

2. Clearing model of electricity market
Independent system operator (ISO) is the main body of clearing and dispatching in wholesale market. The lower layer of the model is ISO's wholesale market clearing model, which achieves the maximum
social benefit under the constraint of power balance. According to the quotation of all power suppliers, the quotation of demand side resource aggregator and the load forecast value, the transaction situation of power suppliers and agents in each period of the next day is determined.

\[
\begin{align*}
\text{min}_t \sum_{M,t} P_{gm,t} - \sum_{N,t} P_{dn,t} + P_{dn,t} - P_{dn,t} \\
\text{s.t} \sum_{M} P_{gm,t} + P_{wn,t} = \sum_{n} P_{dn,t} + P_{dem} \\
\min_{P_{gm,t}} P_{gm,t} \leq P_{gm,t} \leq \max_{P_{gm,t}} (\mu_{k,h}, \overline{\mu}_{k,h}) \\
\min_{P_{dn,t}} P_{dn,t} \leq P_{dn,t} \leq \max_{P_{dn,t}} (\nu_{n,s}, \overline{\nu}_{n,s})
\end{align*}
\]

Where, \(x = (P_{gm,t}, P_{dn,t})\); \(P_{dn,t}\) is the bidding capacity of aggregator \(n\) in time \(t\), \(n \in 1,2,\ldots,N\); \(P_{dn,t}\) is the bidding capacity of generator \(m\) in time \(t\); \(P_{gm,t}^{\max}\), \(P_{gm,t}^{\min}\) are the maximum power and the minimum power of the \(m\)-th generator at \(t\) time correspondingly. \(P_{dem}\) is uncontrollable load; \(P_{wn,t}\) is the forecasting power of the \(n\)-th wind turbine generator at time \(t\). \(P_{dn,t}^{\min}\), \(P_{dn,t}^{\max}\) is the minimum and maximum bid for the \(n\)-th demand side resource aggregator respectively, where \(P_{dn,t}^{\min} = \sum_{i,t} S_{i,t} P_{di,t}^{\min}\), \(P_{di,t}^{\max} = \sum_{i,t} S_{i,t} P_{di,t}^{\max}\); \(\lambda\), \(\mu_{n,s}\), \(\overline{\mu}_{n,s}\), \(\nu_{s,t}\), \(\overline{\nu}_{s,t}\) are Lagrange multipliers.

3. Load model of demand side resource aggregator

3.1. Reference price effect

Reference price effect is an important part of behavioral economics. It was proposed by Kahneman and Tversky (1979) to describe the influence of reference point on people's decision-making. For example, when a user purchases a certain commodity, he will compare the current price with the previous price, which is the reference price. The fluctuation of reference price will affect the purchase decision. When the reference price is higher than the current price, the user will feel "benefit", thus increasing the user's demand; on the contrary, when the reference price is lower than the current price, the user will feel "loss", thus reducing the user's demand.

3.2. Risk preference

In order to analyze the different attitudes of users towards "profit" and "loss", three types of behavioral preferences are introduced in Economics: gain-seeking, loss neutral and loss averse, which respectively represent three types of users. Generally, the utility value [3] is used to quantify the user's attitude.

For the risk preference users, they are more sensitive to the gain, and can get more utility value than the loss neutral and loss averse users under the same gain; for the loss averse users, they are more sensitive to the loss, and feel more loss than the risk neutral and loss neutral users under the same loss.

3.3. Demand side resource load model

Electric power is also a kind of commodity, and restoring the attribute of electric power commodity is the basic requirement of power market reform. Under the influence of the reference price, the load demand model of demand side resource aggregator is as follows:

\[
P_{di,t} = P_{di,t}^{\min} - a_{di} \rho_{di,t} + \eta_{di} \left( \rho_{di,t}^{\min} - \rho_{di,t} \right)
\]

Where, \(\rho_{di,t}\), \(\rho_{di,t}^{\min}\) are the declared price and the reference price of the demand side resources, and the reference price can be the actual price of the previous time; \(P_{di,t}^{\min}\) is the maximum load power of user
i when participating in demand response; \(a_{di}\) is the price elasticity coefficient; \(\eta_{di} (\rho_{di,t} - \rho_{di,j})\) indicates the influence of the difference between the actual price and the reference price on the power demand; \(\eta_{di}\) is the preference of users; In order to accurately reflect the power consumption characteristics of demand side resources, aggregators should also include users' risk preferences when collecting and summarizing users' information. Therefore formula (5) can be written as:

\[
P_{di,j} = P_{m,di,j} - a_{di}\rho_{di,j} + \sum_{k=1}^{3} \text{Pr}_{i,k}\left[\eta_{di,k}^+ (\rho_{di,t}^r - \rho_{di,j}) + \eta_{di,k}^- (\rho_{di,t}^r - \rho_{di,j})\right] \tag{6}
\]

Where, \((\rho_{di,t}^r - \rho_{di,j})^+ = \max\{\rho_{di,t}^r - \rho_{di,j}, 0\}\), \((\rho_{di,t}^r - \rho_{di,j})^- = \min\{\rho_{di,t}^r - \rho_{di,j}, 0\}\), \(\eta_{di,k}^+\), \(\eta_{di,k}^-\) \(\eta_{di,k}^+ \geq 0\), \(\eta_{di,k}^- = (\eta_{di,1}, \eta_{di,2}, \eta_{di,3})\), \(\eta_{di,k} = (\eta_{di,1}, \eta_{di,2}, \eta_{di,3})\). When \(\rho_{di,t}^r - \rho_{di,j} > 0\), take \(\eta_{di,k}^+\); When \(\rho_{di,t}^r - \rho_{di,j} < 0\), take \(\eta_{di,k}^-\). \(k = (1,2,3)\) indicates that users are loss averse, loss neutral and risk preference respectively. Loss averse users are more sensitive to loss than to benefit, thus \(\eta_{di,1}^+ < \eta_{di,1}^-\); Loss neutral users' sensitivity to loss is equal to that of gain, thus \(\eta_{di,2}^- = \eta_{di,2}^+\); Users with risk preference are less sensitive to "loss" than to "gain", thus \(\eta_{di,3}^+ = \eta_{di,3}^-\). \(\text{Pr}_{i,k}\) denotes the three types of probabilities that user \(i\) is loss aversion, loss neutral, and risk preference.

4. Bidding model for demand-side resource aggregators

The decision-making body at the upper level of the model is the demand-side resource aggregator. Under the condition of meeting the constraints of physical characteristics and user comfort, with the goal of maximizing the benefits of aggregating commercial electricity, it declares the prices for each period of the next day to ISO. For ease of description, formula (3.6) is rewritten as:

\[
\rho_{di,j} = k_{di} (z_{di,t} - P_{di,t}) \tag{7}
\]

Formula (7) is the air-conditioning load demand function reported by the user to the aggregator, where \(k_{di} = \frac{1}{a_{di} + \sum_{k=1}^{3} \text{Pr}_{i,k} \eta_{di,k}^+}\), \(\bar{\eta}_{di} = \sum_{k=1}^{3} \text{Pr}_{i,k} \eta_{di,k}^-\), \(z_{di,t} = P_{m,di} + \bar{\eta}_{di} \rho_{di,t}\). \(k_{di}\) Indicates the user’s private information. The user’s utility function \(B(q_{di})\) can be obtained by integrating the quotes \(B(P_{di,t}) = \int \rho_{di,t} dP_{di,t}\). Then the user’s utility function is expressed as:

\[
B(P_{di,t}) = k_{di} [z_{di,t} P_{di,t} - 0.5 P_{di,t}^2] \tag{8}
\]

The upper-level optimization model aims at maximizing the benefit of electricity use, and the objective function is:

\[
\max_{\rho_{iso,t}} B(P_{di,t}) - \rho_{iso,n,t}^2 P_{di,t} \tag{9}
\]

Where, \(P_{di,t}\) is the electricity purchased by the \(n\)-th aggregator at time \(t\); \(\rho_{iso,n,t}\) is the clearing price of node \(n\) at time \(t\); \(B(P_{di,t}) = k_{di} (z_{di,t} P_{di,t} - 0.5 P_{di,t}^2)\), is the utility function of user \(n\). where, \(P_{di,t} = \sum_{i=1}^{l} P_{di,i}, z_{di,t} = \sum_{i=1}^{l} z_{i,t}, k_{di} = \frac{1}{l} \sum_{i=1}^{l} k_{di}\), \(l\) is the number of users managed by the aggregator.
5. Bi-level optimization model transformation based on KKT conditions

In the bi-level optimization model of demand side resource aggregators participating in market bidding, the upper level decides the aggregators' quotation $\rho_{dnt}$ in each period according to the lower level quotation $P_{gm,t}$ and $P_{dn,t}$; In the lower level model, the bid of the generator $P_{gm,t}$ and the bid of the aggregator $P_{dn,t}$ in each period are determined according to the bidding $\rho_{dnt}$ of the upper level aggregator and the bidding of other generators $\rho_{gm,t}$. Jeroslow pointed out that bi-level linear programming is a NP hard problem, which is difficult to solve directly [4-5]. In this paper, KKT method is used to transform the bi-level optimization problem into a single level optimization problem:

$$
\begin{align*}
& \min_{\rho, P, \lambda, \mu, \nu} \left( \sum_{m,t} \rho_{gm,t} P_{gm,t} - \sum_{n,t} \rho_{dn,t} P_{dn,t} + \lambda \left( \sum_{m} P_{gm,t} + P_{wn,t} - \sum_{n} P_{dn,t} + P_{dem} \right) 
+ \mu_m \left( P_{gm,t}^{\min} - P_{gm,t} \right) + \mu_{m,t} \left( P_{gm,t} - P_{m,t}^{\max} \right) + \nu_{m,t} \left( P_{n,t}^{\min} - P_{dn,t} \right) + \nu_{n,t} \left( P_{n,t}^{\max} - P_{dn,t} \right) \right)
\end{align*}
$$

The lower optimization model is transformed into the following constraints by KKT method:

$$
\begin{align*}
& \rho_{gm,t} - \lambda - \mu_{m,t} + \mu_{m,t} = 0 \quad (11) \\
& -\rho_{dn,t} + \lambda - \mu_{n,t} + \mu_{n,t} = 0 \quad (12) \\
& \mu_{m,t} \geq 0, \mu_{m,t} \left( P_{gm,t} - P_{gm,t}^{\min} \right) = 0 \quad (13) \\
& \mu_{n,t} \geq 0, \mu_{n,t} \left( P_{gm,t}^{\max} - P_{gm,t} \right) = 0 \quad (14) \\
& \nu_{m,t} \geq 0, \nu_{m,t} \left( P_{dn,t} - P_{dn,t}^{\min} \right) = 0 \quad (15) \\
& \nu_{n,t} \geq 0, \nu_{n,t} \left( P_{dn,t}^{\max} - P_{dn,t} \right) = 0 \quad (16)
\end{align*}
$$

In the above constraints, (13)-(16) are nonlinear complementary relaxation conditions. In the calculation process, the nonlinear conditions (13)-(16) should be further transformed into linear problems: For the complementarity equation $\pi f = 0$, where $\pi$ is a nonnegative Lagrange coefficient, $f$ is a restricted continuous function($f \geq 0$). Take two binary decision variable $M$ and $w$ to transform the equation $\pi \leq Mw$, $f \leq M(1 - w)$. Formulation (13)-(16) are transformed into a linear inequality, and the transformation results are as follows:

$$
\begin{align*}
& \max_{\rho_{dnt}} B \left( P_{dn,t} - \rho_{dnt} \right) - \rho_{iso,t} P_{dn,t} \quad (17) \\
& \text{s.t.} \quad \mu_{m,t} \leq Mw_{m,t}^\mu \quad (18) \\
& P_{gm,t} - P_{gm,t}^{\min} \leq M \left( 1 - w_{m,t}^\mu \right) \quad (19) \\
& \mu_{m,t} \leq Mw_{m,t}^\mu \quad (20) \\
& P_{gm,t}^{\max} - P_{gm,t} \leq M \left( 1 - w_{m,t}^\mu \right) \quad (21) \\
& \nu_{m,t} \leq Mw_{m,t}^\nu \quad (22) \\
& P_{dn,t} - P_{dn,t}^{\min} \leq M \left( 1 - w_{n,t}^\nu \right) \quad (23) \\
& \nu_{n,t} \leq Mw_{n,t}^\nu \quad (24) \\
& P_{dn,t}^{\max} - P_{dn,t} \leq M \left( 1 - w_{n,t}^\nu \right) \quad (25)
\end{align*}
$$
5th International Symposium on Resource Exploration and Environmental Science  IOP Publishing
IOP Conf. Series: Earth and Environmental Science 781 (2021) 042009   doi:10.1088/1755-1315/781/4/042009

\[ w_{m,t} + w_{n,t}^r \leq 1 \]  \hspace{1cm} (26)

\[ w_{n,t}^c + w_{n,t}^r \leq 1 \]  \hspace{1cm} (27)

6. Case analysis

6.1. Basic data

The user load represented by the aggregator is shown in Table 1 [6]; The parameters of conventional units are shown in Table 2 [7]; The average value of the electricity price data in reference [8] is taken as the reference electricity price \( \rho_r = 45 \$/MW \). User parameters are shown in Table 3.

Table 1. Air conditioning load parameters

| User load | Load (kW) | Number of air conditioning | Refrigeration energy efficiency ratio \( \mu \) | Heat dissipation coefficient \( \varepsilon \) | Thermal conductivity \( A \) |
|-----------|-----------|---------------------------|-----------------|-----------------|------------------|
| value     | 2.5       | 6000                      | 2.7             | 0.96            | 0.18             |

Table 2. Generator set parameters

| Generator | \( P_{g,\text{min}}^\text{max} \) (MW) | \( P_{g,\text{max}}^\text{max} \) (MW) | \( a_g \) | \( b_g \) |
|-----------|--------------------------------------|--------------------------------------|----------|----------|
| 1         | 0                                    | 50                                   | 0.25     | 80       |
| 3         | 0                                    | 50                                   | 0.05     | 83       |
| 3         | 0                                    | 50                                   | 0.28     | 75       |

Table 3. User preference parameters

| User style | \( a_{dn} \) | \( \eta_{dn}^r \) | \( \eta_{dn}^c \) |
|------------|--------------|-----------------|-----------------|
| 1          | 0.1          | 0.2             | 0.1             |
| 3          | 0.1          | 0.15            | 0.15            |
| 3          | 0.1          | 0.1             | 0.2             |

The forecast quotation data of power generation companies adopts the historical quotation data of power generation companies in each period, and takes the average value [64], as shown in Figure 2. The load forecasting is shown in Figure 3.

Figure 1. Forecast value of generators’ biddings
6.2. Analysis of bidding strategy results of demand side resource aggregators
The demand side resource aggregator forecasts the quotation of other generators and quotes the next day's load demand before the day. The quotation strategy of the aggregator is shown in Figure 4, and the load before and after participating in the market is shown in Figure 5.

![Diagram showing user load forecast value](image)

**Figure 2.** User load forecast value

![Diagram showing bidding capacity and bidding price of aggregators](image)

**Figure 3.** Bidding capacity and bidding price of aggregators

![Diagram showing comparison of aggregators' load before and after bidding in the market](image)

**Figure 4.** Comparison of aggregators’ load before and after bidding in the market
The quotation strategy of air conditioning load agent is shown in Figure 4, from which we can see that the quotation of agent is related to the fluctuation of load. In the peak period of 7:00-12:00 and 18:00-2:00, the bidding price is also significantly higher, and in the peak period, the bidding volume of power suppliers is also lower, which helps to reduce the power cost of users and alleviate the power shortage of the system. Figure 5 shows the load of demand side resource aggregators before and after bidding in power market. It can be seen from the figure that when the aggregators participate in the system bidding, they can relieve the load tension at peak hours, effectively reduce the peak valley difference, and contribute to the stability of the power grid.

7. Conclusion

This paper proposes a bi-level optimization model of bidding strategy for demand side resource aggregators to participate in electricity market transactions. Compared with the existing bidding strategy model, the reference effect in behavioral economics is introduced to describe the electricity consumption behavior of consumers. In the bi-level model, the lower level is the wholesale market clearing model aiming at the maximum social benefit, and the upper level is the bidding decision model aiming at the maximum power consumption benefit of air conditioning load. The example shows that the demand side resource aggregator participating in the power market can better achieve the effect of peak load reduction and valley filling, and promote the safe and stable operation of power grid.

Acknowledgements

This study is funded by the science and technology project of SGCC (Mechanism design and key technology research of power market under the new renewable portfolio standard, SGSH0000DJJS2000155).

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