Master-slave game Modeling of Energy subsidy pricing based on demand response

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Abstract. This paper presents a master-slave game model of demand response between power grid companies and multiple users. Firstly, the objective functions of power supplier and power user revenue are established by considering the customer satisfaction and power fluctuation cost. Then, the variables in the model are divided into strategy sets of the two players by the decision variable mapping set technique, and the equilibrium solution is obtained after multiple rounds of games. The example shows that the subsidy price of peak load period can be obtained by the grid company based on the model, and both the grid company and the user can benefit from the demand response.

1. Introduction

With the deepening of coupling of various energy sources and the development of comprehensive energy services, the demand response takes the reduction or translation of electricity load as the core, which can realize the demand transformation among various energy types. Demand side management and demand response of energy power system can provide technical support for the application and practice of comprehensive energy service.

There have been a lot of research on pricing methods at home and abroad. Ref.[1] presents a multi-objective optimization framework for electric vehicle service providers to determine the purchase price of electricity and charging. Ref.[2] established a multi-objective charging optimization model based on time-of-use price, and proposed a charging pricing strategy for electric vehicles. Ref.[3-4] studies the method of setting real-time electricity price for e-commerce sellers from different perspectives by constructing the principal Angle game model between e-commerce sellers and users. Ref.[5] makes a strategy for pricing in real time based on the master-slave game model among different e-commerce sellers. To sum up, although there have been a lot of studies on price setting, there is no relevant research on the price setting of subsidy released by power grid companies in demand response.

For this reason, this paper issues demand response for power grid companies, overcomes the defects of the existing subsidy price formulation scheme, and studies the issue of power grid companies'
demand response subsidy price formulation by establishing a master-slave game model between power grid companies.

2. Benefit analysis

2.1 Supplier profit

\[ R_g = \sum_{k=1}^{T} \left[ (p_k - c_k)q_k - Z \right] - h(q) \]  (1)

In the formula, \( R_g \) represents the income of the power supplier; \( k = 1, 2, \cdots, T \) represents different periods of time within a day; \( p_k \) represents the electricity price within the period; \( c_k \) represents the marginal cost price of power generation within the period; \( q_k \) stands for electricity consumption in the period; \( Z \) stands for user satisfaction cost; \( h(q) \) represents the cost of additional expenses incurred by the company due to fluctuations in the demand for electricity within a day.

2.2 Electricity expenditure

\[ R_y = \sum_{k=1}^{T} p_k q_k + Z \]  (2)

In the formula, \( R_y \) represents the user's electricity purchase expenditure.

2.3 Fluctuating cost of power generation

\[ h(q) = c \sum_{k=1}^{T} (q_k - \bar{q})^2 \]  (3)

In the formula, \( h(q) \) represents the fluctuating cost of power generation, \( c \) represents the fluctuating cost coefficient of power generation, and \( \bar{q} \) represents the average daily generating capacity.

2.4 Customer satisfaction cost

\[ Z = d_k b_k \left[ \left( \frac{q_k}{d_k} \right)^{a_k} - 1 \right] \]  (4)

In the formula, \( d_k \) represents the nominal electricity demand of the user; \( a_k \) and \( b_k \) represent the satisfaction cost correlation coefficient, which is related to the user type.

3. Optimization model construction based on master-slave game

In this section, the income of the power supplier is taken as the game subject, and the expenditure of the power supplier is taken as the game subordinate body. The total decision variables of the model are peak hour price \( p_f \), normal time price \( p_n \) and valley time price \( p_g \) respectively.

3.1 Game strong side module.

As the main body, the power supplier plays a leading role. Its specific income comes from the sale of electric energy, and it is also related to the cost generated by the fluctuation of power generation and the cost of user satisfaction. Specific profits are expressed as follows:

\[ u_i = \sum_{k=1}^{T} \left[ (p_k - c_k)q_k - Z \right] - h(q) \]  (5)

In the formula, \( u_i \) represents the income of the supplier.
3.2 Game weak party module.
Reducing user expenses can prompt users to respond positively to time-of-use price (TOU). The user's expenditure is mainly used for purchasing electricity, and is also related to the cost of user satisfaction. The specific expenditure is expressed as follows:

$$u_2 = \sum_{k=1}^{T} p_k q_k - Z$$

(6)

In the formula, $u_2$ represents the user's electricity purchase expenditure.

3.3 Game constraints.
For the power supplier, while adopting TOU strategy to increase profits, the goal of peak load cutting should also be considered. Constraints are adopted:

$$p_f > p_p > p_g, \quad p_h > c_h$$

(7)

For users, their response to TOU price is limited, and different types of users have different upper and lower limits of response to the price in a certain period of time. Adopt constraints:

$$q_{mi} < q_k < q_{ma}$$

(8)

In the formula, $q_k$ represents the electricity consumption within this period, $q_{mi}$ represents the minimum electricity consumption of the user, and $q_{ma}$ represents the maximum electricity consumption.

At the same time, it is hoped that the peak load of the user demand curve will not increase after the implementation of TOU. Adopt constraints:

$$q_{kmax} < q_{0kmax}$$

(9)

In the formula, $q_{kmax}$ represents the maximum peak charge after the implementation of time-of-use electricity price; $q_{0kmax}$ represents the maximum peak charge before the implementation of time-of-use electricity price.

4. Solution method for model
The model established in this paper can be divided into two parts to solve. The inner layer is weak party strategy space $S_2^i$, the outer layer is strong party strategy space $S_1^i$, and the inner and outer layer strategy space combination after iterative calculation is the TOU.

The above is an internal and external iteration calculation, and the optimal strategy space combination is the initial strategy set of the next iteration. After the $n$th iteration, the fitness function for each policy set is calculated:

$$\theta_i = \|S_{i}^{n} - S_{i}^{n-1}\|$$

(10)

Select the strategy set corresponding to the minimum fitness as the convergence judgment set $S_{min}^n$, and judge whether the game converges. The convergence criterion is as follows:

$$\left|u_i\left(S_{min}^{n+1}\right) - u_i\left(S_{min}^{n}\right)\right| \leq \phi$$

(11)

When $n=0$:

$$u_i\left(S_{min}^{n}\right) = \max\left(u_i\left(S_{i}^{n}\right)\right)$$

(12)

When the above convergence conditions are satisfied after the $n$th iteration, it is considered that the game is over and the optimal time-of-use strategy space is obtained. In the optimization model, the dominant power supplier will obtain higher revenue and satisfaction.
5. The example analysis

5.1 Parameter Settings
An example is given to construct the prediction curve of the next year's annual continuous load based on the historical continuous load curve of a city. It is assumed that the upper limit of power transmission and distribution capacity of the city's power grid is 10000MW. Based on the annual continuous load forecast of the next year, the load value in the first 20h is higher than 10000MW. There may be multiple users willing to participate in the demand response as the grid company issues the demand response. For this reason, the application of the solution proposed in this paper is not limited to the number of users. To simplify the example, only three large users are considered in this paper. The power grid company can avoid the unit cost of transmission and distribution capacity of 100 yuan/(kWh). The loss coefficient of power grid transmission and distribution is 6%. The average market price is 0.85 yuan/(kWh). Electricity price for transmission and distribution is 0.15 yuan/(kWh). The electricity purchase price of each period of the user is 1 yuan/(kWh).

5.2 Results analysis
Based on the above data, simulation programming under MATLAB environment can get the equilibrium solution of the game between the power grid company and the user's master-slave. The subsidized price of demand response made by the power grid company in each period is shown in FIG.1. The load comparison in peak load period before and after the implementation of demand response is shown in FIG.2.

The analysis shows that the optimal strategy of power grid companies is to release demand response projects in the first 6 hours of peak load period, rather than to reduce the load corresponding to all peak load periods. The higher the subsidy price set by the grid company, the higher the response power of the users in the corresponding period.

Under the same response quantity, the response cost of user 1 to 3 increases in turn. It can be seen from FIG. 3 and FIG. 4 that in each demand response period from user 1 to 3, the response quantity decreases in turn, and the demand response income decreases in turn. It indicates that for the same
subsidy price, the lower the response cost of the user is, the greater the response quantity will be and the greater the corresponding demand response benefit will be. In addition, in order to explore the impact of unit cost of avoidable transmission and distribution capacity on demand response income of power grid companies, the calculation example shows that when unit cost of avoidable transmission and distribution capacity gradually changes from 100 yuan/(kWh) to 200 yuan/(kWh), the demand response income of power grid companies gradually changes from 18,466,700 yuan to 52,234,300 yuan.

The results show that, the higher the unit cost of transmission and distribution capacity can be avoided, the greater the motivation for the organization to publish demand response projects. The results are consistent with the actual situation, which verifies the rationality of the game model to a certain extent.

6. Conclusion
In this paper, a game model between power grid companies and multiple users is built based on the master-slave game for power grid companies to issue demand response. The simulation results show that the proposed game model can achieve the stated goal, and the rationality of the model is verified to a certain extent. This article believes that the strategy of subsidizing electricity prices has positive significance for the reasonable use of funds to improve the overall income of its power transmission and distribution companies in the market environment, including improve the load forecasting precision of the power grid companies, use historical demand response data improve accuracy of power grid companies and users demand response revenue model method can be used as a further research content.

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