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Research on bidding strategy of microgrid based on nash game theory

Pei-guang CHEN¹ Kai-fu CHEN² Zi-hao TIAN³

¹Institute of Economic and Technology, State Grid Jilin Sheng Electric Power Supply Company, 1427 Pingquan Road, Nangan District, Changchun, 130062

²College of Physics, Jilin University, Qianjin Street No. 2699, Changchun City, Jilin Province, China, 130012

³Institute of Economic and Technology, State Grid Jilin Sheng Electric Power Supply Company, 1427 Pingquan Road, Nangan District, Changchun, 130062

The corresponding author's e-mail address: 25010753@qq.com

Abstract. Based on the analysis of the characteristics of microgrid power generation, low network loss and low pollution, the microgrid power market is established based on multi-agent theory to solve the power interaction between microgrid (MG) and active power distribution network. Considering an imperfectly competitive power market, the Nash game theory is used to analyze the microgrid bidding strategy. The study found that the MG participating in the bidding can maximize the profit through the bidding strategy with high scale factor and low-cost quotation. Once the bidding strategy of a microgrid is changed, other microgrids will adjust the bidding strategy accordingly. But the electricity trading market will eventually achieve Nash equilibrium. Finally, the bidding strategy and optimal selection scheme of MG's own profit maximization are obtained by using game theory and model.

1. Introduction

The next-generation power grid is considered to be a smart grid architecture. The main driving force for this structure comes from energy efficiency improvement, reduction of greenhouse gas emissions, improvement of power quality and reliability, and distributed power generation and energy storage. The inevitable result of the innovation and sustainable development of advanced power electronics and modern communication technology[1]. In order to operate such an important and complex architecture, MG, as the most important component of smart grid, can realize the integration and coordination of distributed power supply by distributed energy resource management platform.

MG is a small power generation system that distributes electrical energy more flexibly and reliably in smaller geographic areas. They typically utilize distributed energy sources, such as distributed generation units and energy storage facilities, to meet local power needs. As a result, they can reduce their reliance on traditional centralized grids (also known as power grids or backbone networks). In addition to environmental benefits, using existing local renewable energy sources, such as solar cells, fuel cells or wind turbines, MG can reduce transmission and distribution losses because supply and demand sides are adjacent in the ground. It can solve the power demand and supply complementarity in a certain area well. With the continuous maturity of distributed generation and energy storage technologies, MG will be widely used in the future. The establishment of micro grid power trading market is an important way to realize the balance of power supply and demand.



2. Literature review

The concept of distributed generation (DG) was first proposed in the US Public Utility Management Policy Act in 1978. The definition can be summarized as: power generation facilities placed directly in the distribution network or distributed near the load, generating electricity economically, efficiently and reliably[2]. Power generation facilities in distributed generation systems are called distributed power sources, and mainly include wind power generation, solar power generation, fuel cells, and micro gas turbines. These power supplies usually have a small power generation (typically less than 50 MW) and are close to the user. They can generally supply power directly to nearby loads or output power to the grid as needed. This is called distributed power or distributed energy (Distributed Energy Resources, DER) [3].

With the vigorous promotion of clean energy in China and the gradual maturity of distributed generation technology, there will be a trend of diversification in the generation side. There will be more and more independent, scattered and self-serving DER and prosumer (electric power producers, i.e. independent users with DER, participate in the power market competition). The traditional “spontaneous self-use, surplus power online”[4] MG energy trading is no longer suitable for the needs of power market reform, and a new competitive energy trading mechanism is needed to realize the rational allocation of power resources.

Regarding the trading mechanism of the electricity market, many scholars consider the trading problem of the electricity market from the perspective of market equilibrium, and believe that the market equilibrium can be achieved through the electricity market and through the competition between the trading agents and electricity price [5-6]. For the electric energy trading between DER and users in the microgrid and active distribution network, relevant research has been carried out at home and abroad [7-9]. It mainly includes trading mechanism design research [10] and bilateral dynamic trading behavior research [11], but the setting of these price caps is obviously biased towards the user side, and the market is fair, while the ability to adjust the market supply and demand situation is inferior. At the same time, the influence of prediction error is not considered, and the relevant market trading methods are not perfect.

From the concept of MG [12], the driving force for power trading in MGs is usually internal transactions, i.e. power is usually achieved through internal transactions, and excess power can be sold to active distribution networks or inadequate power can be achieved by purchasing power from active distribution networks. In view of the problems in the above research, this paper considers the market bidding mechanism applicable to the multi-operator of MG from the perspective of bidding for electricity sales.

Smart grid pricing has been a very interesting issue in the power market in recent years. Pricing mechanism in electricity market is mainly studied by demand side management (DSM) [13-14] or different bidding models [15-16], mainly for centralized generation [17] and power market services based on auction theory [18]. Although significant progress has been made in distributed generation and MG technology, there is still limited attention to the power bidding mechanism between distributed generations [19]. There are only a small amount of literature on the impact of competition and cooperation among distributed generators on electricity price. Kasbekar and Sarkar consider a scenario with multiple independent MGs close to each other in a region that are connected to each other and to the central grid (macrogrid). In each time slot, a given MG may produce more than, less than or as much power as it needs, and there is uncertainty on which of these events may occur[20]. Zeng et al. [21] establish a loss allocation model in distribution network with distributed generation based on nodal price. The nodal price is to make up for loss cost by merchandise surplus, which allocates residual expenses so as to reduce the marginal loss. According to the characteristics of distribution network, Wang et al. [22] propose the investment cost related pricing based on AC power flow (ICRP-AC) model. The proposed model is adapted to the distribution network investment pricing, and can consider the effects of injected/ absorbed nodal active power and reactive power as well. Ai and Zhang [23] consider the MG bidding optimization strategy based on multi-agent system. Huang and Sarkar [24] examine a MG consisting of multiple generators and propose a generic pricing

mechanism based on the QoS of the power supply inside the microgrid. In particular, a noncooperative game is formulated to capture the competitive market and to study the energy supply strategies of multiple energy suppliers.

Based on the existing research and the current situation of MG, this paper constructs a MG power trading market based on multi-agent system(MAS), and uses Nash game theory to explore the optimization strategy of microgrid bidding strategy. At the same time, according to the market clearing bidding principle, the bidding mechanism and income situation are given.

3. Problem description and model hypothesis

This paper considers a multi-agent MG system that is connected by a large number of power electronic devices such as wind power, small hydropower, solar photovoltaic power generation, gas turbines and other distributed power sources. Combined with the traditional electricity market trading rules and the particularity of the MG, the power market trading model is constructed as shown in Figure 1.

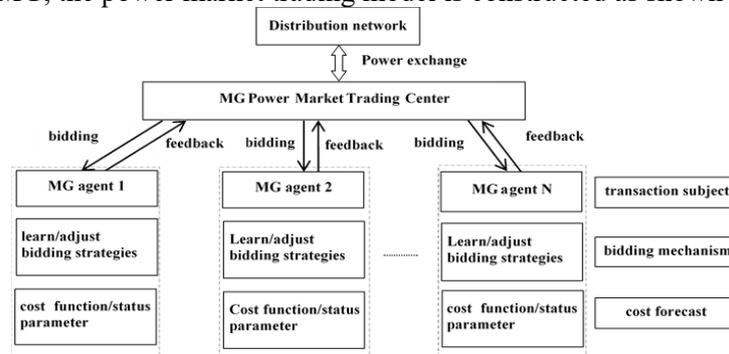


Fig.1 market bidding structure for MG based on MAS

The MG power market trading center determines the market price and realizes market transactions according to the demand situation of the distribution network. Considering the uniqueness of the MG, the power market trading center classifies the MG according to the bidding situation, and divides the MG into the power supplier and the demand side according to the time period, and then feeds back the power demand and supply data in the grid to each MG agent. Finally, the MG market trading center should calculate the balance between the supply and demand of the MG. If the supply of power is less than the demand, it needs to purchase electricity from the distribution network. Otherwise, it can sell the electricity to the active distribution network, and then settle the market. For the MG agent, it mainly predicts its own power generation and load to determine its role in the market (seller or buyer), and returns its relevant data to the MG power market trading center. The trading center gives feedback information to the microgrid agent, and the microgrid agent analyzes it with historical data, formulates its own purchase or sale plan, and uploads the determined purchase, then sale plan to the transaction center.

This article makes the following assumptions:

- (1) Assume that there is a MG participating in the bidding in the MG power trading market, their power generation cost is a quadratic function of output.
 - (2) The market power demand is uncertain, and the MG agent will bid for the cost plus.
 - (3) The cost information between the MGs is asymmetric, that is, the MG agent cannot obtain the cost information of its competitors.
 - (4) The market clearing principle is determined according to the highest quotation of the MG agent.
- Other symbols used herein are described in Table 1.

Table 1. Related symbols and their meanings

Variable	Meaning
i	MG i , $i = 0, 1, 2, \dots, n-1$
ϕ_i	Output of MG i
θ_i	Cost dynamic adjustment factor for MG i
a, b	Representing the secondary and primary cost constant coefficients of the output
C	Power generation cost
h_i, r_i	The type of power generation cost and the number of cost dynamic adjustment factors for the MG
c	Fixed cost of MG power generation
η	Pricing of electricity trading
p_i^m	Corresponds to the C_i^m cost type, $m = 1, 2, \dots, h_i$, and $p_i^1 + p_i^2 + \dots + p_i^{h_i} = 1$
μ_i^l	Corresponds to the θ_i^m cost type, $l = 1, 2, \dots, r_i$, and $\mu_i^1 + \mu_i^2 + \dots + \mu_i^{r_i} = 1$
τ_i	Dynamic adjustment scale factor representing the expected cost of MG i
π_i	Represents the profit of the MG agent i

4. MG bidding model and solution analysis

Assume that there are n MGs in the electricity market to sell electricity, and one of the specific MGs (hereinafter referred to as MG 0) is used as the entry point, and the power generation cost is

$$C(\phi_0) = a\phi_0^2 + b\phi_0 + c \quad (1)$$

Where ϕ_0 is the output of MG0, $C(\phi_0)$ is the production cost of MG0. Due to the uncertainty of the market, these powersellers of MG agents will use cost-plus pricing system according to the changes in the market. In other words, they are in a free market competition environment. According to the principle of economics, when these power sellers participate in bidding, they will make a proportional addition on the basis of the original cost: when the market demand is greater than supply, a scale factor $\theta > 1$ is added to its cost. When the market demand is less than supply, a scale factor $\theta < 1$ is added to its cost, then the cost function of MG 0 is specified by the following equation:

$$C = \theta C(\phi_0) \quad (2)$$

There are $n-1$ MGs except MG0 participating in bidding for electricity sales in the market. Similar to the hypothesis of MG0, the cost function of the i ($i = 1, 2, \dots, n-1$) MG is specified by the following equation:

$$C_i(\phi_i) = \theta_i(a\phi_i^2 + b\phi_i + c_i) \quad (3)$$

It can be seen that the profit of MG 0 is

$$\pi(\phi_0) = \eta\phi_0 - C \quad (4)$$

MG i profit is formulated as

$$\pi(\phi_i) = \eta\phi_i - C_i, \quad i = 1, 2, \dots, n-1 \quad (5)$$

Since MG0 is difficult to know the power generation cost information of other $n-1$ MG bidding power sales agents, MG0 can only predict the probability distribution of power generation cost of these competitors through historical information. The cost expectations of bidding for the sale of electricity MGs can be calculated by probability theory method.

Assume that there are h_i different types of MG i , corresponding to different power generation cost functions. Similarly, there are r_i different types of cost dynamic adjustment factor θ , which also correspond to different probabilities. The relationship between generation cost and cost dynamic

adjustment factor is independent, then the probability distribution of the power generation cost C of the MG and the probability distribution of the cost dynamic adjustment factor θ are p_i^m and μ_i^l respectively, where the value of m is $m = 1, 2, \dots, h_i$ and the value of l is $l = 1, 2, \dots, r_i$.

At this point, MG 0 will compete with many other MGs with uncertain cost dynamic adjustment factors, totaling $\sum_{i=1}^{n-1} h_i r_i$. According to the knowledge of probability theory, when the probability distribution of the power generation cost c_i of the MG i is p_i^m and the probability distribution of θ_i is μ_i^l , the probability of the power generation cost function can be obtained by the formula as $p_{ml}(C_i = C_i^m, \theta_i = \theta_i^l) = p_{ml}(C_i = C_i^m) \cdot p_{ml}(\theta_i = \theta_i^l)$. i.e.

$$p_{ml} = p_i^m \cdot \mu_i^l \tag{6}$$

Therefore, power generation cost of MG i is expected to be

$$E(C_i) = \sum_{m=1}^{h_i} \sum_{l=1}^{r_i} p_i^m \mu_i^l \cdot \theta_i^l C_i^m \tag{7}$$

According to the ideas discussed above, there is also a cost dynamic adjustment factor for the expected cost of the MG i , which is set to τ_i . Therefore, the expected cost addition function of the MG i is $\overline{C_i(\phi_i)} = \tau_i E(C_i)$, that is,

$$\overline{C_i(\phi_i)} = \tau_i \cdot (\overline{a_i \phi_i^2} + \overline{b_i \phi_i} + \overline{c_i}) \tag{8}$$

The profit function of MG i can be obtained in (8)

$$\pi(\phi_i) = \eta \phi_i - \tau_i \cdot (\overline{a_i \phi_i^2} + \overline{b_i \phi_i} + \overline{c_i}) \tag{9}$$

At this point, the bidding game between the MGs is obviously perfect information, so it can be solved by Nash equilibrium. Using the first derivative, the corresponding results are obtained as in Eq.(10) and Eq.(11), and it is easy to judge that the second derivative is less than zero.

$$\partial \pi(\phi_0) / \partial \phi_0 = \eta - \theta(2a\phi_0 + b) \tag{10}$$

$$\partial \pi(\phi_i) / \partial \phi_i = \eta - \tau_i(2\overline{a_i \phi_i} + \overline{b_i}) \tag{11}$$

According to the demand forecast, the MG trading center can get the power load at this time, and then determine the total output of all bidding MG as follows:

$$\phi = \phi_0 + \sum_{i=1}^{n-1} \phi_i + \phi_b \tag{12}$$

Where ϕ_b is the amount of electricity purchased by the grid trading center to the external active distribution network.

Through simultaneous formulas (10), (11) and (12), the optimal bidding capacity of MG0 can be obtained with consideration of competitors' conditions.

$$\phi_0 = (\phi + \phi_b - \frac{1}{2} \sum_{i=1}^{n-1} \frac{\theta \overline{b_i} - \tau_i \overline{b_i}}{\tau_i \overline{a_i}}) / (1 + \sum_{i=1}^{n-1} \frac{\theta \overline{a_i}}{\tau_i \overline{a_i}}) \tag{13}$$

From the formula (2), we can get the expected value of marginal cost of MG 0.

$$\overline{\eta} = \theta(2a\phi_0 + b) \tag{14}$$

By combining (3), (5), (8) into a set of equations, it is possible to estimate that competitors of the MG0 expect to bid for electricity.

$$\overline{\phi_i} = \theta(\eta - \overline{b_i}) / (2\tau_i \overline{a_i}) \tag{15}$$

With the same reason in (11), it can be estimated that the expected price of the MG 0 competitor is

$$\overline{\eta_i} = \tau_i(2\overline{a_i \phi_i} + \overline{b_i}) \tag{16}$$

Obviously, the expected price between MG 0 and its competitors is generally different, but the price in the electricity market is unique. According to the principle of unified clearing price, the bidding price of all MG participants is ranked from low to high, and the highest bidding price is the final clearing price of the power market. Therefore, the clearing price of the market is $\eta^{opt} = \max(\bar{\eta}, \bar{\eta}_1, \dots, \bar{\eta}_{n-1})$, Combining equations (4) and (9), we can get the expected profits of each MG after bidding.

5. Conclusion

In view of the situation that multiple MGs participate in bidding power generation in the electricity market trading center, this paper proposes a multi-agent theory based bidding game model for MG, and gives the strategy of MG bidding in power generation market. It can be seen that the generation cost of MG has a direct impact on participating in bidding, and the MG with higher generation cost is forced to adopt higher quotation. According to the rules of power market trading center, those with low bidding will be given priority to power generation, so as to obtain more profits. At the same time, the research also found that the MG participating in the bidding can maximize its own revenue through the combination of bidding strategies with high scale factor and low-cost quotation, and the change of bidding strategy of one MG will lead to the adjustment of bidding strategies of other MGs. However, the MG power trading market will eventually achieve Nash equilibrium. Finally, the optimal bidding strategy and the optimal scheme for the profit maximization of MG are obtained by numerical analysis, which provides a theoretical basis for MG to obtain higher profits on the basis of considering other competitors.

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