A non-cooperative game theory based energy trading strategy of multi-microgrids

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Abstract. This paper proposes an energy trading strategy based on non-cooperative game theory for multi-microgrids (MGs). According to whether the renewable energy generation can meet the load demand, the MGs are divided into consumers and providers. In order to reduce the operation cost, consumers compete to buy the energy provided by suppliers and changing the price of electricity purchase. The suppliers provide energy according to the priority factor. The energy provided by the provider is distributed to the consumer in proportion to the price offered by the consumer, and the income is allocated to the provider in proportion to the sales volume. On this basis, a non-cooperative game model composed of consumers is built, and the game model has Nash equilibrium is proved. Meanwhile, the Nash equilibrium solution through particle swarm optimization (PSO) algorithm is obtained. Finally, the feasibility and effectiveness of the energy trading strategy are verified by simulations.

1. Introduction

With the global energy and environmental problems becoming increasingly prominent, a large number of renewable energy has installed into the power system. In order to deal with the challenges brought by the randomness and intermittence of renewable energy to the large power grid, microgrids (MGs) have attracted more and more attention. Multi-MGs are the extension of single MG system. The ability of a single MG to ensure the quality of power supply is limited. The combination of multiple MGs can increase the stability of the system. Compared with a single MG, multi-MGs should not only ensure the normal operation of each generation unit in the system under grid-connected and isolated operation, but also take into account the energy flow between the MGs in the system, so as to improve the power supply stability and economy \cite{1}, \cite{2}. Therefore, the coordinated operation of multi-MGs is one of the research focuses.

The traditional energy trading algorithm and market trading mechanism are difficult to meet the individual autonomy requirements of the MGs in the community. As an effective theory to study the selection of optimization strategies in the competitive environment, game theory can greatly improve the autonomy and intelligence of each MGs in the community \cite{3}. In \cite{4-6}, MGs are divided into consumers and providers, and describes the energy flow between MGs as a game problem. Each MG obtains its own optimal operation results in the game process. In the literature \cite{7}, a priority based energy scheduling method is proposed, in which the priority is determined by the previous contribution value of MGs, and the electricity trading power between MGs is determined according to...
the priority. Starvation parameters as an important basis for energy distribution of MGs is introduced in [8]. In the literature [9], a long-term planning of an industrial MG is carried out with the goal of reducing the power consumption cost of the MG. A non-cooperative game model is established to make the consumers play games, and the Nash equilibrium results of the game are given.

The advantage of non-cooperative game is that if there is a Nash equilibrium, it will be very stable. The main contribution of the paper is that a non-cooperative game model composed of consumers for multi-MGs is established, and Nash equilibrium of the game model is proved. The proposed energy trading strategy can optimize the energy flowing among different interconnected MGs.

2. Energy trading strategy of multi-MGs

2.1. Structure of a multi-MGs system

In this paper, a multi-MGs composed of $M$ adjacent MGs is built, and its simplified diagram is shown in Figure 1. Each MG in the community contains different kinds of distributed generation (DG) units and loads. Each MG is connected with each other and has two-way communication lines. It is managed by the global central controller (GCC), which is not only interconnected but also independent. In this system, each MG can get power from adjacent MG in case of insufficient power or provide unused power in case of excess power. If the power in the system is still surplus or insufficient, it can exchange energy with the main power grid.

**Figure 1.** Structure of a multi-microgrids system.

2.2. Proposed trading strategy

In the multi-MGs, there are $M$ MGs, $M = \{MG_1, MG_2, \ldots, MG_M\}$ represent the collection of all MGs in the MG community. Within a certain time $t$, the difference between the renewable energy power generated by MG $i$ and the load power can be defined as net power, i.e,

$$\Delta P_i^t = P_{PV_i}^t + P_{WT_i}^t - P_{load_i}^t$$  \hspace{1cm} (1)

where $P_{PV_i}$, $P_{WT_i}$, $P_{load_i}$ are photovoltaic (PV) units’ output, wind turbine (WT) units’ output and load power of MG $i$ in time $t$ respectively. If $\Delta P_i^t > 0$ in the period of $t$, MG $i$ is called as provider and $J$ is the set of all providers. If $\Delta P_i^t < 0$ in the period of $t$, MG $i$ is called as consumer, and $I$ is the set of all consumers.

The following electricity trading rules are considered: 1) only when the internal renewable energy generation cannot meet the local load demand, the MGs purchase energy from the adjacent MGs; 2)
only when the internal renewable energy generation exceeds the local load demand, the MGs can sell power to the adjacent MGs; 3) the energy purchased by the MGs is not allowed to be resold to other MGs; 4) consumers quote independently, and providers provide energy to consumers according to their bidding proportion; 5) suppliers is ranked according to the priority factor and provide energy to consumers in order.

Assuming \( C_i \) is the price strategy of the \( i \)-th consumer, the energy that consumer \( i \) can get from the electricity trading in \( t \) period can be expressed as follows:

\[
B'_i = \begin{cases} 
-\Delta P'_i, & 0 < E'_B \leq E'_S \quad \text{or} \quad E'_B > E'_S > 0 \quad \text{and} \quad \frac{C'_i}{\sum_{i \in I} C'_i} E'_S > \Delta P'_i \\
\sum_{i \in I} C'_i E'_S', & E'_B > E'_S > 0 \quad \text{and} \quad \frac{C'_i}{\sum_{i \in I} C'_i} E'_S < \Delta P'_i \\
0, & \text{other}
\end{cases}
\]  

(2)

where \( E'_B \) is the total energy required by all consumers in \( t \) period, and \( E'_S \) is the total energy that can be provided by all providers in \( t \) period. At that time \( E'_B < E'_S \), each consumer can get the energy equal to its own power difference, and the remaining energy is sold to the large power grid. At that time \( E'_B > E'_S \), the energy is distributed to each consumer according to the proportion of consumers' bidding.

The supplier, as the seller, will determine its own energy sales according to the priority factor. If the net power of provider \( j \) is \( \Delta P'_j \), then the priority factor can be expressed as:

\[
PR_j = \frac{\sum_{t=1}^{24} (P'_{wt,j} + P'_{pv,j})}{\sum_{t=1}^{24} P'_x}
\]

(3)

The energy sold by provider \( j \) in the process of energy trading can be expressed as follows:

\[
S'_j = \begin{cases} 
\Delta P'_j, & E'_B > E'_S > 0 \quad \text{or} \quad E'_B > E'_S > 0 \quad \text{and} \quad \sum_{j \in J} PR_j E'_B > \Delta P'_j \\
\frac{PR_j}{\sum_{j \in J} PR_j} E'_B', & E'_B > E'_S > 0 \quad \text{and} \quad \frac{PR_j}{\sum_{j \in J} PR_j} E'_B < \Delta P'_j \\
0, & \text{other}
\end{cases}
\]

(4)

If the total energy that providers can provide is less than the total energy demand of consumers, all providers will output all the energy they can provide, otherwise, the providers will output energy according to the proportion of priority factors.

The total revenue received by the provider can be expressed as:

\[
R' = \sum_{i \in I} B'_i C'_i
\]

(5)

The income of provider \( j \) according to the proportion of output energy to total output energy can be expressed as follows:

\[
R'_j = \frac{S'_j}{\sum_{j \in J} S'_j} R'
\]

(6)
3. Non-cooperative game model of multi-MGs

3.1. Non-cooperative game modelling
The basic elements of non-cooperative game include participants, strategy and benefit function. The details are described as follows:

In the non-cooperative game model of energy trading among different MGs i.e., 
\[ G = \{ I; S_1, S_2, \ldots, S_n; U_1, U_2, \ldots, U_n \} \], there are:

1) Participants
Consumer MGs \((i \in I)\) are the participants in the game model. Participants can make decisions independently and strive for the maximum of their own interests in the game process.

2) Strategy
Each consumer MG participates in bidding by changing the price of electricity \((C_i^t)\), so as to control the energy of electricity trading between itself and other MGs, so that its own economic cost is the lowest, and the participants can choose values in the strategy set. All feasible power purchase price strategies of participant \(i\) are defined as follows:

\[ S_i = \left\{ C_i \left| C_i^{\text{min}} \leq C_i \leq C_i^{\text{max}} \right. \right\} \]  \hfill (7)

where \(C_i^{\text{min}}\) and \(C_i^{\text{max}}\) denote the maximum and minimum purchase price of participant \(i\), respectively. \(C_i^{\text{min}}\) is the price for MGs to purchase electricity from the main grid, and \(C_i^{\text{max}}\) is the price for MGs to sell electricity to the main grid. The bidding price of each MG is between the purchase and sale prices of the main grid, and the bidding range is consistent. This definition can ensure that the income of energy trading between adjacent MGs is greater than that of energy trading with the main grid, so that energy flows in the multi-MGs system first.

For participants, the optimal bidding strategy is expressed as follows:

\[ C_i^* = \arg \max U_i(C_i^t, C_i^t) \]  \hfill (8)

where \(C_i\) is the set \(\{C_i, \ldots, C_i^t, \ldots, C_i\}\).

3) Benefit function
In this paper, each MG participating in the game is set out from the economic point of view, on the basis of ensuring its own stable operation, with the minimum economic operation cost as the goal. The objective function expression of minimum cost for consumer MG operation is shown as follows:

\[ \min U_i = \sum_{t=1}^{T} (F_i^t - C_i^t B_i^t) \]  \hfill (9)

Therefore, the benefit function of consumer MG is defined as:

\[ U_i = \sum_{t=1}^{T} \begin{cases} 
-\Delta P_i^t C_i^t, & 0 < E_n^t \leq E_s^t \ or \ E_n^t > E_s^t > 0 \ and \ \sum_{i=1}^{C_i^t} E_s^t > \Delta P_i^t \\
\sum_{i=1}^{C_i^t} E_s^t, & E_n^t > E_s^t > 0 \ and \ \sum_{i=1}^{C_i^t} E_s^t < \Delta P_i^t \\
0, & \text{other}
\end{cases} \]  \hfill (10)

In the non-cooperative game model of multi-MGs, each distributed generation and energy storage unit must satisfy the constraint conditions. MG \(i\) should meet the power balance:

\[ P_{PV}^t + P_{WT}^t + P_{BAT}^t + P_{DE}^t + P_{\text{grid}}^t = P_{\text{load}}^t + \sum_{i \in I} P_{ij} \]  \hfill (11)

When \(P_{ij}\) is a positive value, it represents the energy flowing from MG \(i\) to MG \(j\); when \(P_{ij}\) is negative, it is the energy flowing from MG \(j\) to MG \(i\).

3.2. Nash equilibrium solution solving
When non-cooperative game is used to solve the Nash equilibrium solution, each participant needs to optimize independently according to its own objective function, and each participant's objective
function is coupled with each other. The existing methods to solve the Nash equilibrium solution include iterative search method, eliminating disadvantage strategy method, etc. In this paper, particle swarm optimization (PSO) algorithm is used to solve the Nash equilibrium solution.

Step 1: input system parameters of multi-MGs and configure parameters of each MG, such as wind speed, light intensity, temperature, load power, time of use price of main power grid;

Step 2: establish the multi-MGs game model;

Step 3: initialize the players' strategy $C^0 = \{C^0_1, C^0_2, \ldots, C^0_n\}$, because the game model has Nash equilibrium solution, no matter how to choose the initial value, it will converge to the Nash equilibrium solution;

Step 4: each participant independently optimizes its own strategy by using the single MG optimal dispatching method described in Section II of this paper, and informs other participants of their own strategy. For example, after the $k$-round optimization process, the strategy set of each participant is obtained $C^k = \{C^k_1, C^k_2, \ldots, C^k_n\}$, and each participant uses the PSO algorithm to optimize the next round through arg max decision rules:

$$C^{k+1}_i = \arg\max U_i (C^k_1, C^k_2, \ldots, C^k_n)$$

$$C^{k+1}_2 = \arg\max U_i (C^{k+1}_1, C^k_2, \ldots, C^k_n)$$

$$\ldots$$

(12)

$$C^{k+1}_n = \arg\max U_n (C^{k+1}_1, C^{k+1}_2, \ldots, C^k_n)$$

Step 5: if the two adjacent optimization strategies are consistent, then the combination of the strategies is the Nash equilibrium solution, otherwise, return to the previous step to continue the optimization.

4. Case studies

In this paper, a multi-MGs including three MGs is simulated by Homer software. The configuration results are shown in Table 1. The cost parameters of DGs are shown in Table 2. Time of use price is adopted for the main power grid, as shown in Table 3. The optimal operation results of multi-MGs are obtained by simulations according to the proposed strategy.

The simulation results of net power of the three MGs is shown in Figure 2. According to the definition of consumers and providers in Section 2, it can be seen from the figure that the same MG plays different roles at different times. When the net power is greater than 0, the MG is the provider. When the net power is less than 0, the MG acts as a consumer and selects the bidding strategy to maximize its profit according to the bids of other consumers.

| Table 1. The parameters of each MG |
|-----------------------------------|
| Parameters                        | MG1      | MG2      | MG3      |
| Wind unit capacity(kW)            | 1080     | 571      | 800      |
| PV unit capacity(kW)              | 875      | 403      | 0        |
| Battery capacity(kWh)             | 2000     | 1800     | 1200     |
| Charge/discharge rate of battery(kW) | 200      | 300      | 200      |
| Upper limit of diesel generator output(kW) | 200      | 200      | 100      |
| Lower output limit of diesel generator(kW) | 80       | 80       | 10       |
| Load type                        | Industrial loads | Residential loads | Residential loads |
Table 2. Operation parameters of distributed generations.

| Parameters                      | Wind | PV  | Battery | Diesel generator |
|---------------------------------|------|-----|---------|-----------------|
| Fuel cost (Yuan/kWh)            | —    | —   | —       | a=0.0085, b=0.02, c=6 |
| Operation and maintenance cost (Yuan/kWh) | 0.120 | 0.010 | 0.045   | —               |

Table 3. Time-of-use price.

| Item     | Price / (Yuan/kWh) |
|----------|--------------------|
|          | Peak period | Usual period | Valley period |
| Purchase | 0.83       | 0.49        | 0.27         |
| Sales    | 0.65       | 0.38        | 0.13         |

Figure 2. The Net powers of the three MGs.

The power flow direction among different MGs is shown in Figure 3. If $P_{ij}$ is positive, it represents the energy of MG $i$ flowing into MG $j$; if $P_{ij}$ is negative, it represents the energy of MG $j$ flowing into MG $i$.

Figure 3. The energy flows among the MGs.
The convergence performance of the non-cooperative game model of energy trading in multi-MGs is shown in Figure 4. At the beginning, the value of benefit function, i.e. daily economic operation cost, of each MG varies greatly. When the number of games reaches 24, the value of each MG benefit function almost does not change. At this time, it can be recognized that the non-cooperative game model has reached Nash equilibrium. According to the electricity purchase price in Nash equilibrium state, the operation state of internal generation unit of single MG is calculated by optimizing operation strategy of single MG.

Figure 4. Non-cooperative game process of the MGs: (a) MG 1 benefit profiles, (b) MG 2 benefit profiles, (c) MG 3 benefit profiles.

The electricity trading price of each MG under the Nash equilibrium in the non-cooperative game is given in Figure 5. $C_1$, $C_2$ and $C_3$ represent the bids of MG 1, MG 2 and MG 3 respectively. The dotted line in the figure shows the time of use purchase price of the main grid $[0.13, 0.27]$, $[0.38, 0.49]$ and $[0.65, 0.83]$. The bid price of each MG varies within this range, which makes the income from the electricity trading among different MGs greater than that from the electricity trading between MG and the main grid, enhances the internal energy mobility of MG and reduces the impact on the main grid. When the role of MG is the provider, it does not need to participate in the bidding, and the bidding price is 0. When there is only one consumer and there is no competition environment, the consumer will charge the supplier's electricity according to the price of electricity sold by the MG to the main grid. When the three MGs are all consumers, all three MGs will purchase electricity from the main grid, and there is no competition among the three bidding, so the bidding price is the electricity price of the main grid. When there are two consumers, they will compete with each other and strive to maximize their own interests.
The results of non-cooperative game of energy trading between MGs within a multi-MGs are shown in Figure 6. The broken line in the Figure represents the net power value of MG, and $P_{og}$ represents the surplus or insufficient energy of MG $i$ after energy trading. According to the positive and negative of net power, the three MGs change their roles continuously in different periods of time. They can act as both consumers and providers. It can be seen from Figure 6 that during the period from 7:00 to 16:00, MG 1 will transfer the surplus energy to the other MGs. MG 2 and MG 3 are consumers, and they are participants in the non-cooperative game model and purchase the surplus energy of MG 1 through bidding; in other periods. When the energy of MG 1 and MG 2 is insufficient, and the energy of MG 3 is surplus, MG 3 will provide energy to the other two MGs. By comparing the values of solid line and $P_{og}$, it can be found that energy trading can alleviate the surplus or shortage of energy in a single MG, and the energy flows and absorbs in the multi-MGs first. The remaining or insufficient energy after energy trading is exchanged by a single MG and the main grid. Meanwhile, the stable operation and economic requirements of the MGs are met through reasonable scheduling of batteries and diesel generators.

**Figure 5.** Electricity trading price under Nash equilibrium.

**Figure 6.** Energy game results: (a) MG 1, (b) MG 2, (c) MG 3.
5. Conclusions
In this paper, the MGs in a multi-MGs system are divided into consumers and providers according to the balance between internal power generation and its own load. As a participant in the non-cooperative game model, consumer MGs can compete with other consumers to obtain the energy provided by the provider and maximize its own interests. In the bidding process of MGs, the overall power balance and the constraints of each unit should be considered. It is proved that the non-cooperative model belongs to potential game, so there is Nash equilibrium. The concept of priority factor is proposed to determine the order of energy provided by suppliers, so that the suppliers with high renewable energy penetration rate can provide energy first and obtain higher benefits. The simulation results show that the consumer MG has full autonomy and independent decision-making ability. As a result, the overall interests of the multi-MGs are effectively improved.

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