Cooperative Operation Mechanism of Multi-Energy Microgrids Based on Nash Bargaining Method

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Abstract. With the increasing openness of the electricity sales side of the electricity market, different stakeholders can improve economic benefits through cooperative operation. Aiming at a type of multi-energy microgrid with electricity-heat coupling, this paper proposes a multi-microgrid operating mechanism based on cooperative game. Taking the operating cost of each microgrid's transaction with the distribution network as the breaking point of the negotiation, the Nash bargaining method is used to solve the electric energy transaction volume and revenue transfer between each microgrid, so that the operating cost of each microgrid reaches the Pareto optimal. The total operating cost of all microgrids is minimized. Taking into account the non-convexity of Nash bargaining solution, the bargaining equilibrium problem is converted into two sub-problems and solved with the Yalmip-Ipopt tool. Finally, we proves the effectiveness of the method proposed in this paper by simulation, and provides a reference scheme for the cooperative operation mechanism of multiple microgrids.

Keywords: microgrid, cooperative game, energy trading, Nash bargaining, pareto optimal.

1. Introduction

With the large-scale development of renewable energy and the deteriorating natural environment, micro-grids that can effectively improve energy utilization have emerged [1-2]. Compared with the independent operation of multiple energy systems, the multi-energy micro-grid can realize the coordinated dispatch of multiple energy sources. It can not only improve the flexibility of system operation, but also reduce environmental pollution and greatly improve energy utilization [3].

At present, many scholars have carried out research in this field. Literature [4] focuses on the analysis of the "overall benefits" of the multi-microgrid system, and establishes an optimal scheduling model based on the power transmission between multiple microgrids, and compares the operating costs of the two modes of independent operation and cooperative-ve operation of multiple microgrids to verify the effectiveness of the proposed model. Literature [5], based on the framework of multi-microgrid collaborative operation, not only considers the economics of multi-microgrid operation, but also considers the indicator of comprehensive energy efficiency, and establishes a multi-objective
optimization scheduling model for multi-microgrid systems to ensure comprehensive energy efficiency. Improve the economics of system operation in a certain range of conditions. Literature [6] studied the cooperative operation of multiple photovoltaic microgrids based on the framework of cooperative game, and used the Shapely value method to distribute the revenue of each microgrid, and at the same time increased the revenue of each microgrid and microgrid alliance.

However, literature [4-5] did not thoroughly distribute the income of each microgrid, and the profit distribution mechanism determines the cooperation enthusiasm of each microgrid. The method proposed in the literature [6] will have a large amount of calculation and low efficiency in the case of a large number of microgrids. On the other hand, most articles only focus on the general microgrid, while the research on the multi-energy microgrid is rare. Therefore, this article focuses on a type of integrated energy microgrid containing electricity and heat, and explores a cooperative mechanism to increase the benefits of each participant.

2. Microgrid Model

The scenario studied in this paper consists of multiple microgrids and distribution network, and multiple microgrids are connected by lines. The microgrid is mainly composed of a wind turbine, a CHP, a heat pump, an energy storage battery, and a heat storage tank. The energy flow in the microgrid is shown in Figure 1.

![Schematic diagram of energy flow in microgrid.](image)

### 2.1. CHP

Assuming that a day can be divided into \( T \) time periods, the fuel cost, electricity output and related constraints of the turbine \( i \) can be expressed as:

\[
C_{t, i, \text{CHP}} = \frac{C_{\text{gas}} P_{t, i, \text{CHP}(c)}}{Q_{\text{LHV}} \eta_{\text{MT}}}
\]

\[
P_{t, i, \text{CHP}(e)} = \frac{\left(1 - \eta_{\text{MT}} - \eta_{\text{B}}\right) \eta_{\text{B}}}{\eta_{\text{MT}}} P_{t, i, \text{CHP}(c)}
\]

\[
P_{\min, i, \text{CHP}(c)} \leq P_{t, i, \text{CHP}(c)} \leq P_{\max, i, \text{CHP}(c)}
\]

\[
P_{\min, i, \text{CHP}(c)} \leq P_{t, i, \text{CHP}(c)} - P_{t, i, \text{CHP}(c)} \leq P_{\max, i, \text{CHP}(c)}
\]
Above, $c_{\text{gas}}$ is the unit price of natural gas, $Q_{\text{LHV}}$ is the low heating value of natural gas, $\eta_{MT}$ is the power generation efficiency of the gas turbine, $P_{\text{CHP}}^{\text{e}}$ is the electricity output of turbine $i$, $\eta_{\text{loss}}$ is the heat dissipation loss rate, $\eta_{B}$ is the heating coefficient, $P_{\text{CHP}}^{\text{min}}$, $P_{\text{CHP}}^{\text{max}}$, $\lambda_{\text{CHP}}^{\text{min}}$, and $\lambda_{\text{CHP}}^{\text{max}}$ are the electric output and the upper and lower limits of the ramp rate of turbine $i$.

2.2. Heat Pump

The heat pump can convert electricity into heat. Since it does not consume additional primary energy, its dispatch cost is not considered. The heat pump output and related constraints of the microgrid $i$ in the time period $t$ of the day are as follows:

$$P_{\text{GB}}^{t} = \eta_{\text{GB}} P_{\text{GB}}^{t}$$

(5)

$$P_{\text{GB}}^{\text{min}} \leq P_{\text{GB}}^{t} \leq P_{\text{GB}}^{\text{max}}$$

(6)

Above, $P_{\text{GB}}^{t}$ represents the electric power that the heat pump of the microgrid $i$ needs to consume, $\eta_{\text{GB}}$ is the conversion efficiency of the heat pump, $P_{\text{GB}}^{\text{max}}$ and $P_{\text{GB}}^{\text{min}}$ are the upper and lower limits of the heat output of heat pump of the microgrid $i$.

2.3. Electricity Storage

Assuming that a battery is used as an electric energy storage device, the operating cost and related constraints of the battery are as follows:

$$E_{\text{ES}}^{t+1} = E_{\text{ES}}^{t} + P_{\text{ES}}^{t} \eta_{\text{ES}}^{t} \Delta t - \frac{P_{\text{ES}}^{t} \Delta t}{\eta_{\text{ES}}^{t}}$$

(7)

$$C_{\text{ES}}^{t} = c_{\text{ES}}^{t} P_{\text{ES}}^{t} \Delta t + c_{\text{ES}}^{t} P_{\text{ES}}^{t} \Delta t$$

(8)

$$\begin{cases} 0 \leq P_{\text{ES}}^{t} \leq P_{\text{ES}}^{\text{max}} \\ 0 \leq P_{\text{ES}}^{t} \leq P_{\text{ES}}^{\text{min}} \end{cases}$$

(9)

$$E_{\text{ES}}^{\text{min}} \leq E_{\text{ES}}^{t} \leq E_{\text{ES}}^{\text{max}}$$

(10)

Above, $P_{\text{ES}}^{t}$ and $P_{\text{ES}}^{t}$ are battery charging and discharging power, respectively, $\eta_{\text{ES}}^{t}$ and $\eta_{\text{ES}}^{t}$ are battery charging efficiency and discharging efficiency, $c_{\text{ES}}^{t}$ and $c_{\text{ES}}^{t}$ are charge and discharge cost coefficients, $E_{\text{ES}}^{t}$, $E_{\text{ES}}^{t}$, $E_{\text{ES}}^{\text{min}}$, $E_{\text{ES}}^{\text{max}}$ are battery charge and discharge, respectively. The upper and lower limits of power and capacity.

2.4. Heat Storage

The principles of electricity storage and heat storage are basically similar, except that what is stored is thermal energy, which will not be repeated here.

2.5. Power Interaction

The power interaction constraints between microgrids and between microgrids and distribution grids are as follows:
\[ C'_{i,EG} = \hat{x}_{EG,cell} \max (P'_{i,EG}, 0) \Delta t + \hat{x}_{EG,buy} \min (P'_{i,EG}, 0) \Delta t \]  \quad (11)

\[ -P'_{i,EG} \leq P'_{i,EG} \leq P'_{i,EG} \max \]  \quad (12)

\[ -P'_{i,j} \leq P'_{i,j} \leq P'_{i,j} \max \]  \quad (13)

Above, \( P'_{i,EG} \max \) represents microgrid \( i \) and the main grid, \( P'_{i,j} \max \) represents the interactive power upper limit of microgrid \( i \) and microgrid \( j \), \( \hat{x}_{EG,cell} \) and \( \hat{x}_{EG,buy} \) are electricity sale price and electricity purchase price of distribution network, respectively.

### 2.6. System Constraints

Each microgrid needs to meet the balance of electricity and heat supply and demand:

\[ P'_{i,CHP(e)} + P'_{i,ES(d)} + P'_{i,EG} + P'_{i,j} \geq P'_{i,GB(e)} + P'_{i,ES(e)} + P'_{i,e} \]  \quad (14)

\[ P'_{i,CHP(h)} + P'_{i,GB(h)} + P'_{i,HS(d)} \geq P'_{i,HS(e)} + P'_{i,h} \]  \quad (15)

Above, \( P'_{i,e} \) and \( P'_{i,h} \) respectively represent the electrical load and thermal load of the microgrid \( i \) in a day.

### 3. Nash Bargaining Method

Compared with the independent operation of microgrids, multiple microgrids can form a cooperative alliance through signing a treaty, and further use the means of electric energy interaction to achieve advantages such as reducing transactions with the distribution network and energy coordination and complementation, which can further increase the benefits of the alliance. This paper establishes a multi-microgrid cooperative operation model based on the Nash bargaining method. This method simultaneously satisfies Pareto optimality, independent and independent selection, linear transformation invariance, and symmetry. The solution goal can be expressed as:

\[ \max \prod \left( C_i - C_i^0 \right) \]  \quad (16)

\[ s.t. \quad C_i \leq C_i^0 \]

Above, \( C_i^0 \) represents the cost of independent operation of microgrid \( i \) within one day, and \( C_i \) represents the operating cost of microgrid \( i \) participating in the cooperative game within one day.

Considering that equation (16) is a non-convex problem that is not easy to solve, the problem is transformed into the following two convex sub-problems for solution:

\[ \min \sum_i C_i \]  \quad (17)

\[ \max \sum \ln (C_i^* - C_i^0 + Z_i) \]  \quad (18)

Equation (17) shows that the total operating cost of the microgrid should be minimized as much as possible. The operating variables of the microgrid obtained from equation (17) are substituted into
equation (18) for further solution; equation (18) aims to solve the Payment transfer, so as to achieve the Pareto optimal of all microgrids.

4. Results Analysis

Three microgrids are used as research scenarios, suppose all microgrids operate independently as mode 1, and cooperative operation as mode 2. The wind turbine output and load curve of each microgrid are shown in Figure 2. The specific parameters can be referred to [7]. Use MATLAB Yalmip-Ipopt tool to solve, get the optimized output of all microgrids in the two modes and the interactive power between each microgrid in mode 2, as shown in Figure 3 (a) and (b) respectively (Due to limited space, the equipment optimization efforts of each microgrid in the two modes are only listed as CHP). And Table 1 shows the comparison of the profits of each microgrid under the two modes.

![Fig. 2. The wind turbine output and load curve of each microgrid.](image1)

![Fig. 3. The optimized output of all microgrids in two modes. and the interactive power between the microgrids in mode 2.](image2)

It can be seen from Figure 3 that all microgrids have improved the output of the internal equipment of each microgrid through cooperation, effectively avoiding a large amount of wind abandonment when all microgrids are in independent operation. On the other hand, all microgrids reduce the cost of equipment output in each microgrid through the complementation of electric and thermal energy.
Table 1. The profits of each microgrid under the two modes.

|        | Mode 1/yuan | Mode 2/yuan | Payment transfer/yuan |
|--------|-------------|-------------|-----------------------|
| MG1    | 6911.70     | 6368.53     | -305.67               |
| MG2    | 7679.54     | 7136.37     | +848.85               |
| MG3    | 5034.67     | 4491.50     | -543.17               |
| Total  | 19625.91    | 17996.40    | 0                     |

It can be seen from Table 1 that when the microgrid is in mode 2, the total cost of the microgrid is reduced by 1659.52 yuan compared with that of mode 1, and the operating costs of all microgrids have been reduced. These three microgrids make the reduced operating costs of each microgrid equal through payment transfer and achieve Pareto optimization.

5. Conclusions

1. This paper proposes a cooperative operation mechanism between multi-energy microgrids (considering electricity-heat coupling), and this method can effectively reduce the total cost of microgrids operation.
2. The Nash bargaining method used can reduce the cost of each microgrid, and all microgrids participating in cooperation have reached Pareto optimal.
3. The method proposed in this paper will not significantly increase the computational cost as the scale of the microgrids increases.

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