Economic Optimization of Multiple Microgrids System Based on Alliance Theory

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Abstract. Aiming at the problem of economic operation of multiple microgrids system, a coordinated optimized operation method of multiple microgrids in integrated energy system based on alliance theory was proposed. Firstly, energy storage station was introduced into multiple microgrids optimal scheduling, the energy flow relationship between various links was studied, and an economic optimal dispatch model was established under the alliance mode of multiple microgrids and energy storage station; Secondly, constructed a Shapely value benefits distribution mechanism to carry out the initial benefits distribution of the alliance and the secondary distribution of the multiple microgrids internal benefits. Finally, taking a typical daily scenario as an example, the optimal operation scheduling strategy of multiple microgrids with the participation of energy storage station was obtained. The results showed that the method proposed in this paper can effectively improve the benefits of all participants and ensure the economic operation of multiple microgrids, at the same time, it realized the full consumption of renewable energy.

1. Introduction
With the diversified development of energy demand on the user side, the coupling relationship between cooling, heating and electricity is becoming closer and closer, and the regional integrated energy system [1-3] has been rapidly developed, it can effectively improve the utilization rate of primary energy through step utilization of different grades of energy, and has received extensive attention in the research field at home and abroad [4]. Multiple adjacent integrated energy microgrids appear in the same large industrial park, forming a multiple microgrids system, and after the energy storage station is connected to the system, the flexibility of the energy storage station to charge and discharge can be used to realize the economic and reliable operation of the multiple microgrids in the industrial park and promote the consumption of renewable energy [5-7].

In this paper, the electricity storage and heat storage are simultaneously introduced into the scheduling decision of multiple microgrids system, multiple microgrids and energy storage stations are formed into an alliance to realize the economic operation of the system, and the Shapely value method is used for the initial distribution of alliance benefits and the secondary distribution of multiple microgrids income, so as to seek the fairness and rationality of the benefits of each participant.
2. Modeling of Integrated Energy System Structure and Equipment

2.1. Integrated Energy System Construction

The microgrid of the integrated energy system constructed in this paper contains four types of energy sources: cold, heat, electricity, and gas. The schematic diagram of its energy supply structure is shown in Figure 1.

![Energy supply structure of integrated energy system.](image)

Figure 1. Energy supply structure of integrated energy system.

It can be seen from the figure that there are three types of loads in the integrated energy microgrid: cooling, heating, and electricity. The main energy supply equipment includes: fans, photovoltaics, gas turbines, waste heat recovery boilers, gas boilers, electric boilers, absorption chillers and electric refrigeration equipment. Energy storage station include electricity storage station and heat storage station. Energy between the microgrid and the energy storage station is a two-way interaction, the energy conversion direction of the equipment is irreversible, and the energy of the microgrid cannot be sent back to the energy network.

2.2. Modeling of Equipment

2.2.1. Modeling of Gas Turbine. The electric power and heating power generated by the gas turbine are shown in the following formula:

\[
P_{MT}(t) = \eta_{MT} L_{NG} V_{MT}(t) \tag{1}
\]

\[
H_{MT}(t) = \frac{P_{MT}(t)(1-\eta_{MT})}{\eta_{MT}} C_{MT} \tag{2}
\]

where \( P_{MT}(t) \), \( H_{MT}(t) \) are the electric power output of the gas turbine and residual heating power of flue gas; \( V_{MT}(t) \) is the natural gas consumption per unit time of the gas turbine; \( L_{NG} \) is the low calorific value of natural gas; \( \eta_{MT} \) is the power generation efficiency, equal to 0.3; \( C_{MT} \) is the waste heat recovery coefficient, equal to 0.8.

2.2.2. Modeling of Absorption Refrigerator. The absorption refrigerators use the heat energy which in the waste heat recovery equipment for cooling, and the output function expression is as follows:

\[
C_{AC}(t) = H_{AC}(t) \eta_{AC} \tag{3}
\]

where \( C_{AC}(t) \) is the cooling power of the refrigerator; \( H_{AC}(t) \) is the heating power consumed by refrigerator; \( \eta_{AC} \) is the cooling coefficient, equal to 1.2.
In addition, the efficiencies of electric and gas boiler are all 0.9, and the energy efficiency ratio of electric refrigeration device is 3.

3. Optimization Model of Multiple Microgrids in Alliance Mode

In order to promote the formation of the alliance, the following two conditions need to be met:

- For an alliance composed of multiple entities, the overall revenue should be higher than the sum of the revenues of the individual entities when they decide to operate independently.
- For each entity, after participating in the alliance, they can obtain greater benefits than when they make individual decision-making operations.

3.1. Optimization Objective

After forming an alliance between multiple microgrids and energy storage station, the system will be optimally dispatched with the goal of the alliance's maximum revenue, and the objective function is:

\[ \nu(S) = \max \{-C_{buy}(P_{\text{grid}}, V_{\text{gas}}, H_{\text{heat}}) - C_a\} \]  

(4)

where \( C_{buy} \) is the energy purchase cost of the alliance; \( C_a \) is the cost of abandoned electricity; \( P_{\text{grid}}, V_{\text{gas}}, H_{\text{heat}} \) are the alliance's purchase of electricity, gas and heating from the energy network.

The expression of \( C_a \) is:

\[ C_a = \sum_{i=1}^{n} \sum_{t=1}^{T} \lambda \cdot \left[ (P_{i,\text{PV}}^{\text{max}} + P_{i,\text{WT}}^{\text{max}}) - (P_{i,\text{PV}}' + P_{i,\text{WT}}') \right] \]  

(5)

where \( P_{i,\text{PV}}', P_{i,\text{WT}}' \) are the actual outputs of the fans and photovoltaics; \( P_{i,\text{PV}}^{\text{max}}, P_{i,\text{WT}}^{\text{max}} \) are the maximum outputs of fans and photovoltaics respectively; \( \lambda \) is the unit cost of abandoned electricity.

3.2. Constraint Conditions

3.2.1. Constraints of Energy Flow

\[ P_{i,\text{Load}}' = P_{i,\text{PV}}' + P_{i,\text{WT}}' + P_{i,\text{grid}}' - P_{i,\text{MT}}' - P_{i,\text{EC}}' - P_{i,\text{EB}}' + P_{i,\text{ES,dis}}' - P_{i,\text{ES,ch}}' \]  

(6)

\[ H_{i,\text{Load}}' = H_{i,\text{heat}}' + H_{i,\text{MT}}' + H_{i,\text{GB}}' + H_{i,\text{EB}}' - H_{i,\text{AC}}' + H_{i,\text{ES,dis}}' - H_{i,\text{ES,ch}}' \]  

(7)

\[ C_{i,\text{Load}}' = C_{i,\text{EC}}' + C_{i,\text{AC}}' \]  

(8)

where formulas (6) to (8) are the balance constraints of electric, heating and cooling power; \( P_{i,\text{Load}}', H_{i,\text{Load}}', C_{i,\text{Load}}' \) are the electric, heating and cooling load of the microgrid \( i \) respectively; \( P_{i,\text{ES,dis}}', P_{i,\text{ES,ch}}', H_{i,\text{ES,dis}}', H_{i,\text{ES,ch}}' \) respectively refer to the selling and discharging power of the energy storage station to microgrid \( i \), as well as the selling and purchasing heat power.

3.2.2. Constraints of Equipment Output

\[ P_{\text{min}} \leq P_i \leq P_{\text{max}} \]  

(9)

where \( P_{\text{min}}, P_{\text{max}} \) are the lower limit and upper limit of the outputs of the energy conversion device.
3.2.3. Constraints of Energy Storage Station

\[
\begin{align*}
S_{\text{min stor}} \leq S_{\text{stor}}(t) & \leq S_{\text{max stor}} \\
U^r_{i,\text{PES,dis}} & \leq P^r_{i,\text{ES,dis}} \leq U^r_{i,\text{PES,dis}} P_{\text{ES,dis}}^\text{max} \\
U^r_{i,\text{PES,ch}} & \leq P^r_{i,\text{ES,ch}} \leq U^r_{i,\text{PES,ch}} P_{\text{ES,ch}}^\text{max} \\
0 & \leq U^r_{i,\text{PES,dis}} + U^r_{i,\text{PES,ch}} \leq 1 \\
U^r_{i,\text{PES,dis}} & \in [0,1], \quad U^r_{i,\text{PES,ch}} \in [0,1] \\
S_{\text{stor}}(t_{\text{end}}) = S_{\text{stor}}(0) & = 20\% S_{\text{stor}}^\text{max}
\end{align*}
\]  

where \( S_{\text{min stor}}, S_{\text{max stor}} \) are the minimum and maximum energy stored by the electrical storage device respectively; \( U^r_{i,\text{PES,dis}}, U^r_{i,\text{PES,ch}} \) are the discharge and charge status bits, which are 0-1 variables, and the same device is unique in the charge and discharge state at the same time. Heating storage devices have similar constraints as electrical storage devices.

3.2.4. Constraints of Energy Purchase from the Energy Network

\[
0 \leq A_{\text{part},j} \leq A_{\text{part},j}^\text{max}
\]

where \( A_{\text{part},j}^\text{max} \) is the maximum value of the type \( j \) energy purchased by microgrid \( i \).

4. Profit Distribution Mechanism Under Multiple Microgrid Optimization

4.1. Shapely Value Distribution Model of Alliance Net Income

After the alliance is formed, it is assumed that the revenue between multiple microgrids system and energy storage station can be transferred, and the Shapely value method is used for revenue distribution. The Shapely value emphasizes that each participant will get the income corresponding to the average contribution of the affiliated alliance, and the distribution result is unique. Assuming that the distribution vector of \( N \) members participating in the alliance is \( (X_1, X_2, X_3, \ldots, X_n) \), the distribution result of each individual member is determined by the following formulas:

\[
X_i = \sum_{S \in \mathcal{N}, i \in S} W(S) (\nu(S) - \nu(S \setminus i))
\]

\[
W(S) = (|S| - 1)! (n - |S|)! / n!
\]

where \( |S| \) is the number of individuals forming the alliance \( S \), \( \nu(S) \) is the income of alliance \( S \), \( \nu(S \setminus i) \) is the income of alliance not including individual \( i \); \( W(S) \) is the average contribution factor.

4.2. Revenue Distribution Scheme of Multiple Microgrids

Firstly, consider multiple microgrids as a whole, form an alliance with energy storage station, and carry out the initial benefit distribution of the alliance according to the Shapely value distribution model. Secondly, redistribute each microgrid according to the total revenue generated by participating in the alliance after the formation of the whole microgrid. The distribution process is shown in figure 2.

5. Analysis of Example

5.1. Example System Settings

The example system used in this paper contains three microgrids, of which microgrid 1 is CCHP system, microgrid 3 is CHP system, and microgrid 2 is a distribution system with only photovoltaic power generation. The electricity storage station is connected to each microgrid, while the heat storage
station is only connected to microgrids 1 and 3. The parameters of TOU power price referenced literature [5], TOU heat price is shown in table 1, and the price of natural gas is 2.5 Yuan/m³.

![Figure 2. Benefit distribution process.](image-url)

**Table 1. Parameters of heat price.**

| Periods | Peak       | Flat       | Valley     |
|---------|------------|------------|------------|
| Time    | 05:00—12:00| 12:00—17:00| 00:00—05:00|
| Time    | 17:00—22:00| 22:00—24:00|             |
| Heat price/(yuan/(kW·h)) | 0.32 | 0.28 | 0.20 |

In order to simplify the analysis, this paper converts both cooling energy and heating energy according to electricity equivalent. Figure 3 is renewable energy and multi-energy loads forecast data graph of the system.

![Figure 3. Forecast curve of various loads and renewable energy outputs in multiple microgrids.](image-url)

### 5.2. Optimization Results

When multiple microgrids and energy storage station form an alliance for optimal scheduling, multiple microgrids can use the flexibility of energy storage station to achieve the purpose of peak clipping and valley filling and energy space-time translation, so as to reduce the purchase of energy from energy network by system, ensure the economic efficiency of multiple microgrids at the peak price of energy network, and promote the total consumption of renewable energy. Figure 4 shows the energy interaction between storage station and multiple microgrids and that between storage station and energy network.

### 5.3. Results of Income Distribution

#### 5.3.1. Initial Income Distribution between Multiple Microgrids and Energy Storage Station

After the formation of a cooperative alliance, the total income of the alliance should be greater than the sum of the income of the participants when they are independent. In order to ensure the stability of the alliance, the alliance income needs to be redistributed after cooperation. Therefore, in this paper, the
Shapely value method is used to distribute the profit for the first time to the alliance composed of multiple microgrids and energy storage station. Table 2 shows the benefit distribution process of multiple microgrids, \( S_{es} \) represents multiple microgrids set, \( S_{st} \) represents energy storage station set.

It can be seen from table 2 that the revenues of the multiple microgrids system and energy storage station are:

\[
I_{es}=0.5\times(-18238)+0.5\times(-8617)=-13427.5 \text{ Yuan}
\]

\[
I_{st}=(-8617)-(-13427.5)=4810.5 \text{ Yuan}
\]

That is, the multiple microgrids system need to pay a total cost of 13427.5 Yuan, while energy storage station will get a profit of 4810.5 Yuan. It can be seen that after the formation of the alliance, the payment cost of multiple microgrids has been reduced, and the energy storage station has obtained a considerable profit, which indicating that this cooperation model can achieve multiple microgrids and energy storage station Win-win between.

5.3.2. Secondary Distribution of Income. Since the example used in this paper contains three microgrids, it is necessary to obtain the benefits of the small alliance formed between the two microgrids. When microgrid 1 & 2 form an alliance, the revenue is -10259.9 Yuan; when microgrid 1 & 3 form an alliance, the revenue is -8032.8 Yuan; when microgrid 2 & 3 form an alliance, the revenue is -9434 Yuan.

On the basis of obtaining the benefits of the small alliances, use equations (12) & (13) to distribute the benefits to each microgrid. The benefit distribution process of microgrid 1 is shown in table 3.
According to the profit distribution process of microgrid 1 shown in table 4, calculate it by Shapely value method, and the payment cost of microgrid 1 is 4352.4 Yuan. Similarly, it can be calculated that the payment cost of microgrid 2 is 5616 Yuan, and the payment cost of microgrid 3 is 3459.1 Yuan. It can be seen from figure 3b that the electric load of the microgrid 2 is large, and there is a large shortage of renewable energy. Therefore, it is necessary to purchase a large amount of electricity from the energy network, resulting in a higher payment cost than the microgrid 1 and the microgrid 2. Therefore, the cost allocation of each microgrid under the Shapely value method is fair and reasonable.

6. Conclusion
In this paper, the optimal operation of multiple integrated energy microgrids system is studied. Firstly, an integrated energy storage station with electricity and heat storage is established, the energy storage station and multiple microgrids are formed into an alliance to participate in dispatching, and propose the optimized operation strategy of the system. Then adopt the Shapely value distribution model, put forward the initial benefit distribution of alliance benefits and the secondary distribution of multiple microgrids system benefits, so as to ensure a balanced and reasonable distribution of interests of all parties. The results of the examples show that the alliance between multiple microgrids and energy storage station can actively mobilize the flexibility of energy storage station, improve the economics of system, ensure the interests of both parties, and at the same time, it achieved complete consumption of renewable energy.

Acknowledgments
This work is supported by National Natural Science Foundation of China (NO.51577068) and SGCC Science and Technology Project “Research on Key Technologies of Energy Internet Town in Xiongan New Area” (NO.5204BB19000N).

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