Optimal energy sharing model for multi-microgrids integrated into the distribution network

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Abstract. With the large-scale integration of clean energy resources, microgrids have shifted from consumer to prosumer. Therefore, the behavior of microgrids would have an enormous impact on the distribution network and electricity market. In this context, this paper established an optimal energy sharing model for multi-microgrids under the condition of the constructing cooperative alliance relationship. An overall operation strategy to maximize clean energy utilization and overall benefits is constructed by a two-stage robust model considering the uncertainty of clean energy. Also, a Shapley model is established to distribute the profit based on the contribution among multi-microgrids. Finally, a test case is applied to demonstrate the effectiveness of the proposed model and is given to verify that the economic benefits of each microgrid are improved after optimization.

1. Introduction

With the development of clean energy, the integration of various distributed generation enables microgrids to produce energy and participate in power market transactions [1-2]. As it is difficult for a microgrid to meet market access rules, it will become inevitable for multi-microgrids to form an alliance to participate in market competition. How to establish a cooperative relationship and formulate an operation strategy to realize the optimal sharing is of significance.

At present, the research on microgrid mainly adopts the method of coordination and optimization. Lin et al. established the multi-period dynamic optimal scheduling model of microgrid with cold and hot electric power supply [3]. By optimizing the internal energy storage device and energy conversion device, energy consumption and operating cost of microgrid are reduced. Cheng et al. studied the influence of different operating modes of ice storage air conditioning on the optimization, and put forward an optimal scheduling model of cold, heat and electricity combined microgrid with ice storage air conditioning [4]. Liu et al. proposed an energy sharing model between energy storage and clean energy and constructed a real-time demand response model based on game theory [5]. Liu et al. put forward the hybrid energy sharing framework of cogeneration and clean energy, which realized the reduction of production cost and the improvement of cogeneration benefit [6]. In Ref. [3-4] mainly focused on the internal operation mode of the microgrid, and improved economic benefits by optimizing its own operation mode, but without regard to the access of clean energy and the interaction among multi-microgrids. In Ref. [5-6], on the basis of considering the access of clean energy, adopt the coordinated interaction of multi-microgrids to realize the absorption of clean energy and the improvement of the microgrid benefits, but are still limited to the method of optimizing itself.
In this paper, considering the situation of the power market, the internal and external two-layer purchase and sale mode [7] and the optimized sharing mechanism between multi-microgrids are adopted to improve the economic benefits of the microgrid through market means. The internal and external purchase of electricity in multi-microgrids will generate profits margin between internal and external selling electricity price. Based on this, this paper constructs a joint optimization mechanism between multi-microgrids. Under the condition of considering the external energy consumption characteristic of each microgrid, the objective function is built to maximize clean energy utilization and overall benefits. The robust model is applied to optimize the uncertainty of wind energy, and the Shapley method [8] is established to distribute the profit of internal and external electricity price difference. Finally, an example is given to verify that the optimal energy sharing model of this paper has an impact on maximizing the benefit of each microgrid.

2. Cooperation alliance for multi-microgrids

In this paper, the optimal energy sharing model among multi-microgrids is divided into two parts for analysis. The first part is the internal components of each microgrid, and the second part is the optimal energy sharing mechanism between multi-microgrids.

2.1. Internal components in each microgrid

The internal components of the microgrid are shown in Figure 1, including traditional load, wind turbine, gas turbine (GT), price-sensitive demand response (PSDR) and other controllable units. The integrated management center forecasts the electricity consumption and output of the next day according to the weather forecast and historical load data. After realizing the internal balance, the external electricity consumption characteristic curve of each microgrid is uploaded to the center. Considering the goal of maximizing clean energy utilization and overall benefits, the center formulates the optimal operation strategy and allocates the differential benefit.

2.2. Optimal energy sharing mechanism between multi-microgrids

The relationship chart of cooperative alliance is shown in Figure 2. The specific optimization process can be divided into the following three stages: first, the microgrid transmits its energy characteristic curve to the integrated management centre. Then, the center combines the external energy characteristic curves of each microgrid to optimize and obtain the optimized operation strategy. Finally, each microgrid buys and sells electricity based on the operation strategy of the center, and allocates the price difference generated by internal and external purchase and sale of electricity based on the distribution model.
3. The optimal operation model for multi-microgrids

3.1. Optimal objective function

The optimal objective function $G_i$ of the microgrid $i$ is as follows, aiming at maximizing clean energy utilization and overall benefits:

$$G_i = \sum_{t=1}^{T} \left[ \left( R_s^i + R_m^i + R_p^i \right) - \left( C_b^i + C_e^i + C_{PSDR}^i + C_{GT}^i + C_{TD}^i \right) \right] \tag{1}$$

In the microgrid $i$ at time $t$, where $R_{si}^i$ denotes the internal electricity sales revenue, $R_{sm}^i$ denotes the revenue from electricity sales in the market, $R_{re}^i$ is the subsidies for clean energy power generation, $C_{bi}^i$ is the internal power purchase cost, $C_{mb}^i$ is the market purchase cost, $C_{PSDR}^i$ denotes the flexible load cost, $C_{GT}^i$ denotes the GT cost, $C_{TD}^i$ indicates the wheeling cost for selling electricity.

3.1.1. Electricity purchase income and power generation subsidies.

$$\begin{align*}
R_{si}^i &= \psi_i^s q_{si}^b \\
R_{sm}^i &= \psi_i^{ms} q_{sm}^m \\
R_{re}^i &= \psi_i^{re} q_{re}^w 
\end{align*} \tag{2}$$

In the microgrid $i$ at time $t$, where $\psi_i^s$, $\psi_i^{ms}$ and $\psi_i^{re}$ are the internal selling electricity price, market selling electricity price and clean energy output subsidy, $q_{si}^b$ is the amount of electricity sold internally, $q_{sm}^m$ is the amount of electricity sold in the market, $q_{re}^w$ is the output of wind power.

3.1.2. Purchasing cost and wheeling cost.

$$\begin{align*}
C_{bi}^i &= \psi_i^b q_{bi}^b \\
C_{mb}^i &= \psi_i^{mb} q_{mb}^m \\
C_{TD}^i &= \psi_i^{TD} (q_{bi}^b + q_{mb}^m) 
\end{align*} \tag{3}$$

Where $\psi_i^b$, $\psi_i^{mb}$ and $\psi_i^{TD}$ are the internal purchasing price, market purchasing price and the wheeling cost for the electricity sales, $q_{bi}^b$ is the amount of electricity purchased internally, $q_{mb}^m$ is the amount of electricity purchased in the market.

3.1.3. PSDR and GT cost. The flexible load adopted in this paper mainly considers the price factor, which can reduce the output burden of the microgrid by reducing the load when the internal power is insufficient. The cost of GT mainly consists of three parts, including the cost of starting and stopping point of the GT, the production cost of continuous power generation and the penalty cost of emission of pollution gas. The cost formula of PSDR and GT are in the literature [7] and [9].

3.1.4. Internal electricity purchase and sales price. The internal purchase and sale price for transactions among multi-microgrids is between the market purchase and sale price. The internal purchase and sale price is determined by the relationship between the supply and demand ratio (SDR) of wind power generation and internal load in the microgrid. The specific situation is as follows:
$$S_{i, DR}^{\text{min}} \leq \sum_{m=1}^{M} q_{i,m}^w \leq S_{i, DR}^{\text{max}} \quad \forall i \in I, \forall t \in T$$

$$w_{i}^t = w_{i}^t + (w_{i}^m - w_{i}^s)(1 - S_{i, DR}^{\text{max}})$$

$$S_{i, DR}^{\text{min}} < 1$$

$$S_{i, DR}^{\text{max}} > 1$$

$$q_{i,m}^w + q_{i,m}^s = q_{i,m}^{\text{load}} \quad \forall i \in I$$

$$q_{i,m}^{\text{load}} = q_{i,m}^{\text{load}} \quad \forall i \in I$$

$$d_{i}^{\text{load}} \geq 0$$

$$\sum_{i=1}^{I} q_{i,m}^w + \sum_{i=1}^{I} q_{i,m}^s = \sum_{i=1}^{I} q_{i,m}^{\text{load}}$$

$$\sum_{i=1}^{I} q_{i,m}^w = \sum_{i=1}^{I} q_{i,m}^s \quad \forall t \in T$$

$$q_{i,m}^{\text{load}} = \sum_{j=1}^{J} q_{i,m,j}^b \quad \forall i \in I, \forall t \in T$$

$$q_{i,m}^{\text{load}} = \sum_{j=1}^{J} q_{i,m,j}^b \quad \forall i \in I, \forall t \in T$$

Where $w$ is the internal selling price, $S_{i, DR}$ is the SDR between electricity and load in the microgrid at time $t$ and $d_{i}^{\text{load}}$ is the load demand.

### 3.2. Constraints

#### 3.2.1. Power purchasing and selling constraints.

In the microgrid $i$ at time $t$, $Q_{i}$ is the surplus power that microgrid $i$ can participate in the internal and the market transactions; $Q_{i}^{\text{min}}$, $Q_{i}^{\text{max}}$ are the minimum and maximum values of surplus electricity.

#### 3.2.2. Power balance constraint.

$$q_{i}^w + g_{i}^{\text{GT}} + Q_{i}^{\text{load}} + q_{i}^{\text{mb}} + q_{i}^{\text{b}} = q_{i}^{\text{load}} + q_{i}^{\text{ms}} + q_{i}^{s}$$

In the microgrid $i$ at time $t$, where $g_{i}^{\text{GT}}$ is the sum of GT forces of each segment, $Q_{i}^{\text{load}}$ is the load reduction of PSDR when power shortage occurs, $q_{i}^{\text{load}}$ is the daily load.

#### 3.2.3. Settlement constraints

$$0 \leq q_{i,j}^{s} \leq Q_{i,j}^{\text{load}} \quad \forall i \in I, \forall t \in T$$

$$0 \leq Q_{i,j}^{\text{load}} \leq Q_{i,j}^{\text{min}} \quad \forall i \in I, \forall t \in T$$

$$0 \leq q_{i,j}^{m} \leq d_{i,j} \quad \forall i \in I, \forall t \in T$$

$$0 \leq Q_{i,j}^{\text{max}} \leq d_{i,j} \quad \forall i \in I, \forall t \in T$$

$$0 \leq q_{i,j}^{b} \leq q_{i,j}^{\text{max}} \quad \forall i \in I, \forall t \in T$$

$$0 \leq q_{i,j}^{m} \leq q_{i,j}^{\text{min}} \quad \forall i \in I, \forall t \in T$$

$$q_{i,j}^{m} = \sum_{j=1}^{J} q_{i,j}^{m,j} \quad \forall i \in I, \forall t \in T$$

$$q_{i,j}^{b} = \sum_{j=1}^{J} q_{i,j}^{b,j} \quad \forall i \in I, \forall t \in T$$

Where $q_{i,j}^{b}$ and $q_{i,j}^{m}$ are the electricity sold and brought from microgrid $i$ to microgrid $j$.

### 3.3. Optimization model

When the center proposes the optimal operation strategy, it needs to consider the uncertainty of clean energy output inside each microgrid. Therefore, the proposed optimal operation strategy needs to deal with the risks caused by uncertain factors. The optimization model of this paper is realized by constructing a two-stage robust model. The uncertainty set is used to characterize the volatility scene of wind power output. After transforming the model into min-max-min form, it can be decomposed into main problems and sub-problems. The min model is used to optimize the output of internal controllable units in the worst scenario, and to formulate the optimal operation strategy in the worst scenario. After solving and linearizing, the CCG algorithm is used to determine the iterative solution. The formula for minimizing the cost of microgrid is as follows:

$$f(x) = \min_{x} f_{1}(x) + \max_{\xi \in Z} \min_{y \in \Omega(x, \xi)} f_{2}(y, \xi, x)$$

(8a)
\[ x = (q^i_t, q^m_t, g^b_t, q^m_t, u^a_t, u^b_t, s_t, \text{GT}_i, \text{GT}_i^\text{off})^T \]
\[ y = (Q, s^i_t, s^o_t, g^m_t)^T \]
\[ \min_x f_i(x) = \sum_{t=1}^{T} \left( C^i_t + C^m_t + C^b_t + C^c_t \right) - \lambda^\text{SUC}_{q^m_t} u^a_t + \lambda^\text{SUD}_{q^m_t} u^b_t + \left( R^a_t + R^b_t + R^c_t \right) \]
\[ s.t. \quad (5), \quad (7a) - (7c) \]

Where \( x \) and \( y \) are the set of decision variables, \( u^\text{GT}_i \), \( u^\text{GT}_i^\text{off} \), and \( u^\text{GT}_i \) are binary variables, representing the starting, stopping and working status of GT of microgrid \( i \) at time \( t \). \( \lambda^\text{SUC}, \lambda^\text{SUD} \) are the startup and shutdown costs of GT during operation, \( q^W_{it} \) is the wind power output under the worst scenario \( \xi \), given that \( x \) and \( \xi \) are known, the feasible domain of variable set \( y \) is \( \Omega(x, \xi) \); \( q^\text{out}_{it} \) is the quantity of cutting load when power supply is insufficient, \( \eta^\text{out}_{it} \) is the corresponding penalty cost.

The uncertain set \( Z \) of wind power output fluctuation scenario is:
\[ Z_i = \left\{ z^W_{it} = z^W_{it} - z^W_{it} \left( \tilde{q}^W_{it} - z^W_{it} \right) \right\} \quad (9a) \]
\[ \forall t \in T \quad \forall i \in I \]
\[ \sum_{t=1}^{T} \left( z^W_{it} - z^W_{it} \right) \leq \Gamma_i \quad (9c) \]

Where \( Z_i \) is the set containing wind power output \( q^W_{it} \) in microgrid \( i \), \( \tilde{q}^W_{it}, q^W_{it} \), and \( z^W_{it} \) are the predicted values of wind power output and the upper and lower limits of fluctuation range contained in microgrid \( i \), \( z^W_{it} \) and \( z^W_{it} \) are variable coefficients of wind power scenario, \( \Gamma \) is the adjustment parameter for wind power uncertainty in the optimization process, and the value range is \([0,1]\).

To sum up, equations (1) - (9c) constitute the whole system model, in which optimization decision variables are summarized as follows: \( q^s_i, q^m_i, q^b_i, q^m_i, u^a_t, u^b_t, u^a_t, u^b_t, s_t, \text{GT}_i, \text{GT}_i^\text{off} \). The optimization model is a mixed integer linear programming problem. The entire algorithm in this paper is implemented in MATLAB 2016a platform and solved reliably using CPLEX12.6.

4. Profit distribution based on Shapley model

Under the optimization model of this paper, the center need to ensure that the microgrid obtains fair economic benefits. When the microgrids in the system cooperate fully, the exchanged power among microgrids and between each microgrid and the distribution network will be determined according to the unified scheduling model, and the corresponding income will be allocated by using the Shapley method. Besides, this allocation method also reflects the size of each microgrid contribution to the entire system, which is conducive to promoting each microgrid to make greater contributions in the transaction. The detailed model is shown in literature [10], which will not be repeated here.

5. Case study

5.1. Calculating examples

In this paper, three microgrids are used to form the system. As shown in Table 1, the internal controllable units of each microgrid are different. The GT is TAU5670 and the specific parameters are shown in the literature [11]. The baseline load accounts for 10% of the total load of the microgrid and the parameters related to the cost coefficient are detailed in the literature [9].
Table 1. The internal components of the microgrids.

| Subject   | Wind | GT  | Flexible load |
|-----------|------|-----|---------------|
| Microgrid 1 | ✓    | ×   | ✓             |
| Microgrid 2 | ✓    | ✓   | ✓             |
| Microgrid 3 | ✓    | ✓   | ×             |

5.2. Analysis of purchasing and selling electricity

It can be seen from Figure 3 - Figure 5 that after the optimization and sharing, each microgrid has some of the externally sold electricity converted to internal sales, which reduces the GT power generation and the emission of polluting gas, and realizes the maximum consumption of clean energy.

Due to the volatility of wind power, at night (4-8h), the wind power output is large, and the load is small. Each microgrid maximizes the consumption of clean energy by selling power to the grid. However, in the morning (8-12h), the wind power output is relatively small, and the load is large. All microgrids purchase electricity from other microgrids or grid to ensure the stability and safety of power supply. In the afternoon (12-20h), the wind power output gradually increases, the load remains peak, and each microgrid can achieve stable power supply through external power purchase or GT power generation.

5.3. Economic benefit analysis

According to the unit price of electricity purchase and sale in microgrid and market are shown in Table 2 and Figure 6, the income of each microgrid is as follows:

It can be seen from Table 3 that after the multi-microgrids participates in the optimization sharing, it reduces its own cost compared with the single operation, and obtains specific sales revenue. Compared with microgrid 2, microgrid 1 and 3 have a relatively large cost reduction, because they reduce their costs by purchasing power from microgrid 2. Each microgrid also achieves additional revenue by allocating the difference profit, so participating in the optimization sharing has great significance for each microgrid.
| Time interval       | Attribute | Purchase price (¥/(kWh)) | Selling price (¥/(kWh)) |
|---------------------|-----------|--------------------------|-------------------------|
| 23:00-07:00         | Valley    | 0.17                     | 0.13                    |
| 10:00-14:00 17:00-23:00 | Peak      | 0.83                     | 0.75                    |
| 07:00-10:00 14:00-17:00 | Flat     | 0.49                     | 0.45                    |

**Figure 6.** Internal purchase and sale price of electricity

Table 3. Price before and after optimization (¥).

| Subject       | Pre-optimization costs | Optimized costs | Pre-optimization benefits | Optimized benefits | Pre-optimization total costs | Optimized total cost |
|---------------|------------------------|-----------------|---------------------------|--------------------|-----------------------------|---------------------|
| Microgrid 1   | 13900.8                | 11900.8         | 1507.6                    | 2107.3             | 12393.2                     | 9793.5              |
| Microgrid 2   | 14686.9                | 12686.9         | 0                         | 23.6               | 14686.9                     | 12663.3             |
| Microgrid 3   | 5246.6                 | 2246.6          | 164.0                      | 264.2              | 5082.6                      | 1982.4              |

6. Conclusions
This paper proposed an optimal energy sharing model for multi-microgrids and a distribution model is established. The following conclusions can be drawn based on the proposed study: the economic benefits of each microgrid have been improved after the energy sharing, and based on a Shapley value method, the costs and benefits of each microgrid are related to some extent, rather than entirely independent. Therefore, the relationship between them should be comprehensively considered.

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