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OPTIMAL OPERATION STRATEGY OF INTERCONNECTED MICROGRIDS IN MARKET ENVIRONMENT

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ABSTRACT

With the advancement of market-oriented reform and the development of microgrid technology, the interconnected microgrids will play an important role in industrial parks, development zones and other scenarios. This paper establishes an operating mode structure of interconnected microgrids in the market environment and proposes a two-layer optimal operation strategy for interconnected microgrid. In the lower layer, the interconnected microgrids system aims at minimizing the total purchase cost of the system and optimize the clearing power price and the power allocation of microgrids, considering the voltage and power flow constraints of the system. In the upper layer，the microgrid operators optimize the bidding strategy with maximum profit, consider feedback from inner optimization. The genetic algorithm and mixed integer programming solver of Cplex is used to solve the model. The case study verifies the effectiveness of the proposed method in different scenarios.

Keywords: interconnected microgrids, renewable energy, electricity market, operation

1. INTRODUCTION

With the maturity of distributed renewable energy power generation technology and the promotion of micro-grid, microgrids in industrial parks or development zones are connected to each other to form an interconnected microgrid, achieving energy mutual assistance and decentralizing operation and management control. The power generation of a high proportion of renewable energy in a single microgrid is affected by weather and other factors, resulting in frequent mismatches between the generation side and the load side. The operation mode of the interconnected microgrid can naturally solve the problem that the load and power generation that are difficult to solve in a single microgrid, including the complement of energy peaks and valleys, the stability of the system, the full use of renewable energy, and the reduction of non-renewable energy and energy storage.

Literature [1] uses non-cooperative game method to study the quotation of transactions between microgrids in loose group mode, concluding that when the probability of power shortage is the same, the microgrid with large power surplus probability can propose higher quotation. Literature [2] guides the distributed microgrid to participate in the microgrid through the market dynamic pricing mechanism. District energy trading has improved the social and economic benefits of the microgrid community and the ability to dissipate distributed energy. A hybrid stochastic/robust optimization model is proposed in [3] to minimize the expected net cost and maximize the profit of the microgrid in both day-ahead and real-time markets. A day-ahead optimal scheduling method for a grid-connected microgrid based on energy storage (ES) control strategy is proposed in [4], to adapt to different types of electricity markets and pricing mechanisms. A three-stage algorithm based on coalitional game strategy is proposed in [5] consisting of request exchange stage, merge-and-split stage and cooperative transaction stage. MGs can minimize their expenditures and ensure the cost efficiency of the whole MGs network with local power transaction. In [6], the bidding strategy of aggregator is optimized by a risk-constrained mean-variance model at the upper real-time market level, and an event-driven mechanism is presented to reach the cleared quantity of the upper market while realizing maximum economy at the lower market level.

This paper establishes the operating mode structure of interconnected microgrids in the market environment,

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proposes a two-layer optimized operation strategy for interconnected microgrid. In the lower layer, the interconnected microgrids is aimed at minimizing the total purchase cost of the system and optimize the clearing power price and the power allocation of microgrids, considering the voltage and power flow constraints of the system. In the upper layer， the microgrid operators optimize the bidding strategy with maximum profit, consider feedback from inner optimization. The genetic algorithm and mixed integer programming solver of Cplex is used to solve the model. The case study verifies the effectiveness of the proposed method in different scenarios.

2. INTERCONNECTED MICROGRIDS OPTIMIZATION OPERATION MODEL

2.1 Structure of the interconnected microgrids

The energy and information interaction structure of the interconnected microgrids is shown in Fig1. The transaction and control center of interconnected microgrids (TCIM) is responsible for communicating with the microgrids and the operation and clearing of the market. The microgrid operators formulate bidding strategies with the goal of maximizing their benefit, and submit bids to the TCIM to eliminate or mitigate the imbalance between supply and demand in the microgrid. The TCIM also purchase electricity at the marginal price $\pi_{\text{sub}}(t)$ form the retail market and the constraints of the transmission line need to be meet.

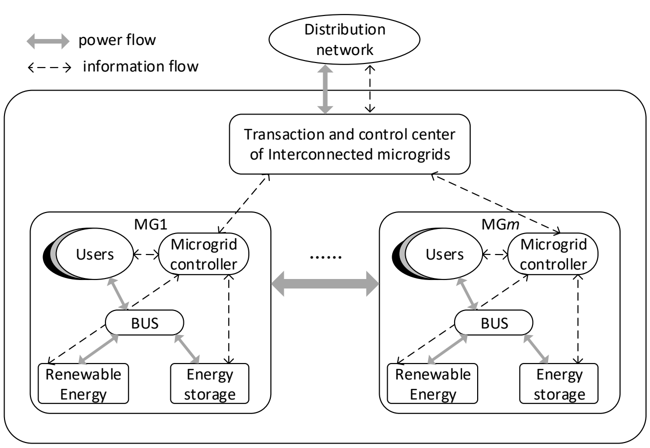

Fig 1 the interaction structure of the interconnected microgrids

2.2 Microgrid operator optimization model

Microgrid operators maximize their own revenue by changing their bidding strategies. The objective function is as follows:

$$\max\sum_{t=1}^{N_{\text{T}}}\left(P_{\text{MG},\ m}(t)\lambda(t)-\sum_{h=1}^{N_{\text{H}}}\alpha_{m,i}P_{MG}{}^{2}(t)+\beta_{m,i}P_{MG}(t)+\gamma_{m,i})\right) \quad (1)$$

Where, N_{T} indicates the total number of bidding periods, in the current power market, the value is generally 24. $P_{\text{MG},\ m}(t)$ indicates the winning bid of microgrid operator *m* in the *t* period, and the product of the market clearing price is the electricity sales revenue during this period, the power generation cost of the microgrid operator *m* is represented by a quadratic function; α_m， β_m and γ_m are the power generation cost coefficients.

The electricity price reported by the microgrid operator m needs to be within the upper and lower limits of the allowable range:

$$\pi_{\text{MG},m}^{\min}\le\pi_{\text{MG},m}\le\pi_{\text{MG},m}^{\max} \quad (2)$$

Considering the possibility of alliances in different microgrids, the operation goal of the alliance is to optimize the quotations of different internal microgrids to maximize the overall benefits. The objective function is:

$$\begin{aligned}\max\sum_{m=N_{\text{s}}}^{N_{\text{e}}}\sum_{t=1}^{N_{\text{T}}}&(P_{\text{MG},\ m}(t)\lambda(t)-\\&\sum_{h=1}^{N_{\text{H}}}\alpha_{m,i}P_{MG}{}^{2}(t)+\beta_{m,i}P_{MG}(t)+\gamma_{m,i})\end{aligned} \quad (3)$$

Where N_{e} and N_{T} are the first and last microgrids in the alliance, respectively, satisfying $1\le N_{\text{s}}\le N_{\text{e}}\le N_m$, where N_m is the total number of microgrids participating in the bidding in the system.

2.3 Interconnected microgrid optimization model

The optimization variable of the interconnected microgrids system is the power purchased by each microgrid operator and the power retail market. The core lies in how to allocate the winning power of each power seller. At the same time, the operational constraints of the power distribution system are also considered to achieve the goal of minimizing the total cost of purchasing electricity. The economic dispatch model is expressed as:

$$\min\sum_{t=1}^{N_{\text{T}}}[\sum_{m=1}^{N_m}P_{\text{MG},m}(t)\pi_{\text{MG},\ m}(t)+P_{\text{sub}}(t)\pi_{\text{sub}}(t)] \quad (4)$$

$$\text{s.t. } P_{\text{G}i}-P_{\text{D}i}=U_i\sum_{j\in i}U_j(\text{G}_{ij}\cos\theta_{ij}+\text{B}_{ij}\sin\theta_{ij}),\forall i \quad (5)$$

$$Q_{\text{G}i}-Q_{\text{D}i}=U_i\sum_{j\in i}U_j(\text{G}_{ij}\sin\theta_{ij}\text{-B}_{ij}\cos\theta_{ij}),\forall i \quad (6)$$

$$U_{\min}\le U_i\le U_{\max},\quad\forall i \quad (7)$$

$$\begin{aligned}P_{ij}=|U_iU_j(\text{G}_{ij}\cos\theta_{ij}+\text{B}_{ij}\sin\theta_{ij})-U_i^2\text{G}_{ii}|\le P_{l\max},\\\forall i,\forall j\in i,\forall l\end{aligned} \quad (8)$$

$$P_{\text{MG},m}^{\min}\le P_{\text{MG},m}(t)\le P_{\text{MG},m}^{\max}\ ,\ \forall m,\forall t \quad (9)$$

$$P_{sub}^{min} \le P_{sub}(t) \le P_{sub}^{max} \ , \forall m, \forall t \qquad (10)$$

Where equation (5) is the objective function of the interconnected microgrid system; $P_{sub}(t)$ is the power that the interconnected microgrids purchases from the power retail market during the *t* period; (6)-(7) are the power flow equations of the distribution system. P_{Gi} and Q_{Gi} represent the active and reactive power output from the power generating unit at node *i*, P_{Di} and Q_{Di} represent the active and reactive loads at node *i*, respectively. (8)-(11) represent the constraint of voltage of node *i*, the constraint of power flow of line l, microgrid operator bid power constraints and the power purchase constraints form the electricity retail market.

3. SOLUTION OF THE BI-LEVEL OPTIMIZATION MODEL

The optimized operation model of the interconnected microgrids is established as a two-layer optimization model, which is the microgrid operator optimization model(MOOM) and an interconnected microgrid optimization model(IMOM). The flow chart of the two-layer optimization method proposed is shown in Fig2.

IMOM is a typical mathematical program with equilibrium constraints(MPEC). The MEPC is transformed into a mixed integer programming problem using KKT conditions and solved by the Cplex solver.

Solving the MOOM is to find the optimal bidding strategy for the microgrid operator *m* to quote the remaining operators. Assume that the microgrid operators can know each other's quotation intervals based on historical transaction data and the node marginal price of day-ahead market. The genetic algorithm is used to solve the problem. For the microgrid operator *m*, firstly randomly generating *n* individuals within the range of their quotations, each representing a quotation strategy. Then $S_m = \{\pi_{m1}(t), \pi_{m2}(t), \ldots, \pi_{mn}(t)\}$ represents a collection of all quote strategies of the microgrid operator *m* at time *t*. For each individual *i*, if the remaining gamer strategies are fixed, the strategy set is substituted into the IMOM to obtain the $P_{MG,m}$ of the microgrid operator *m* and the market clearing price $\lambda(t)$ under the strategy, then calculate the corresponding benefit $R_{MG,mi}$ and individual fitness. Through the selection, crossover and mutation of the individual population, the optimal quotation strategy for the microgrid operator *m* for the remaining operators can be obtained.

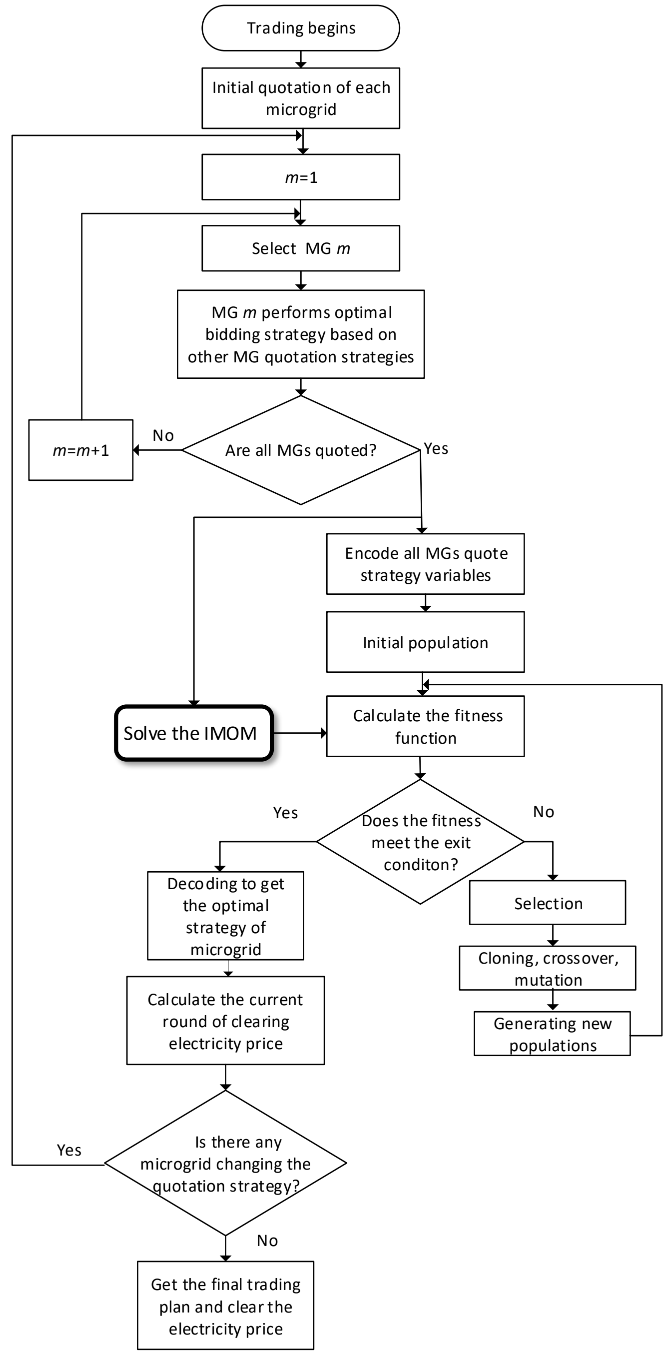

Fig 2 The flow chart of the two-layer optimization method

For the game problem $G = \{S_1, \ldots S_m; R_{MG,1}, \ldots R_{MG,m}\}$, when the formula (11) is established, the market reaches the Nash equilibrium:

$$R_{MG,m}[\pi_m^*(t), \pi_{-m}^*(t)] \ge R_{MG,m}[\pi_m(t), \pi_{-m}^*(t)] \qquad (11)$$

Where, the superscript "*" indicates the optimal quote of the microgrid operator; the subscript "*-m*" indicates the remaining game player in addition to the microgrid operator *m.*

4. CASE STUDY

The IEEE 33 system is used for operational simulation of interconnected microgrids, including three microgrids, located at nodes 12, 24, and 30, respectively. The load demand during simulation period is 2.6+j1.6 MVA. The marginal price of electricity market nodes is 0.0762 USD/(kWh); the bidding power range of 3 microgrids is set to 0~2 MW; The range of electricity purchased in the wholesale market is 0~3 MW; the upper and lower limits of the voltage in each node of the distribution system are 0.95~1.05 pu.

Table 1 Parameters of microgrids in different scenario

Scenario	MG operator	Cost coefficients （USD/kWh）		
		α	β	γ
	1	0.000064	0.025	0
1	2	0.000064	0.025	0
	3	0.000064	0.025	0
	1	0.00004	0.025	0
2	2	0.00025	0.025	0
	3	0.00064	0.025	0

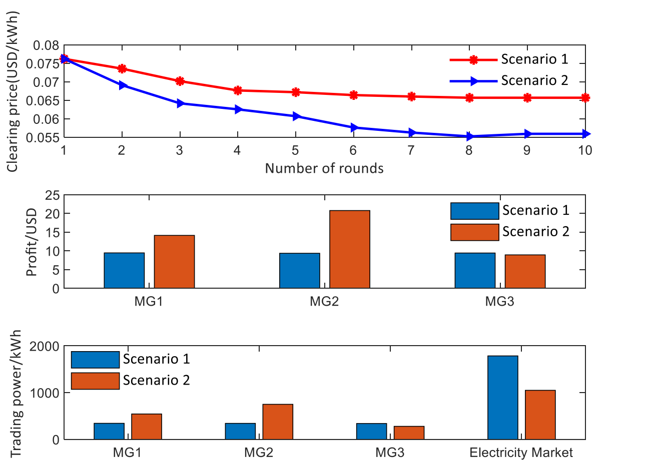

Fig 3 Electricity price, profit and trading power of microgrids in scenario 1 and scenario 2

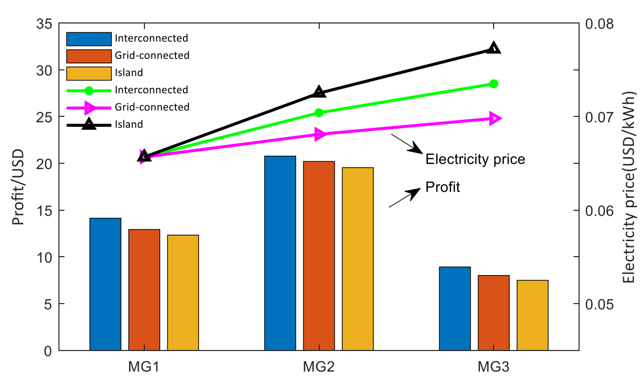

Fig 4 Electricity price and profit of microgrids in state of interconnected, grid-connected and island

Fig 3 shows that the clearing electricity price of the interconnected microgrids decreases with the game rounds increase, and reaches the Nash equilibrium within 10 rounds. Comparing Scenarios 1 and 2, the bidding price is more intense due to the cost change of power generation. Finally, the clearing price of Scenario 2 is lower than Scenario 1, and the profit and the winning bid are increased. Fig 4 shows the electricity price and profit of the microgrid in state of interconnected, grid-connected and island. In the interconnected state, the microgrid has the lowest electricity price and the largest profit. Because The internal transaction of the unbalanced power of the interconnected microgrid can reduce the purchase of electric energy from the distribution network, increase the sales revenue of the unbalanced electricity, and achieve the complementarity of the unbalanced electricity between the microgrids in the interconnected microgrid.

5. CONCLUSION

This paper establishes a two-layer optimized operation model for interconnected microgrid. Case study show that the proposed method can effectively solve the bidding optimization operation problem of the interconnected microgrids, and realize the optimal distribution of the benefits of all parties while ensuring the economic and safe operation of the system.

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