Research on energy transaction mode of regional microgrid cluster and distribution network considering wind power uncertainty

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Abstract. In order to reduce the unnecessary energy interaction between the microgrid and the distribution network, while promoting the local accommodation of wind power, this paper presents an energy transaction mode of regional microgrid cluster and distribution network. Firstly, the mode integrates the load demand and wind power output in the area based on regional multi-microgrid operator. And then, the transaction mode uses the load transfer rate to describe the user response of time of use (TOU) price. Meanwhile, the mode also establishes a model for the TOU price of regional microgrid cluster system considering the uncertainty of wind power. Finally, an NSGA-II algorithm is used to solve the multi-objective optimization problem in the model. Based on the experimental results, the transaction mode achieves cost reduction of microgrid cluster, while reducing unnecessary interaction between the regional microgrid cluster system and the distribution network.

1. Introduction
Currently, energy demand sharply increases while environmental issues become severer. Therefore, distributed wind power is widely employed in power system [1]. Among various ways of integrating distributed wind power, microgrid attracts the most attention as it can effectively coordinate distributed wind power, energy storage, and load [2-3]. However, the increasing microgrids that connected to the distribution network have significant impact on the distribution network operation. Therefore, how to integrate multiple microgrids to promote the utilization of wind power while alleviating the operation pressure of the distribution network needs to be addressed [4-5].

A lot of researches have been carried out on the economic operation of independent microgrid [6-7]. Research [6] presented the economic dispatch strategy under different operational scheduling modes. The authors compared the impact of different operational scheduling modes on the economic operation of the microgrid. In recent years, researches [8-9] focused on multi-microgrid. Considering TOU price, research [8] presented a distributed model predictive control algorithm for the optimal operation of series-structured optical storage multi-microgrid. In research [9], a particle swarm optimization algorithm was applied to coordinate the control of multiple microgrids in periods of peak, flat, and valley. The authors also investigated the economic scheduling method for multi-microgrid system.

The above researches mainly consider the economic operation of the microgrid itself. Few researches focus on the friendly interaction between the microgrid and the distribution network. In
addition, the requirements of the local accommodation of wind power and the reduction of the cost of electricity in the regional microgrid need to be satisfied. Motivated by the previous researches, this paper presents an energy transaction mode for regional microgrid cluster and distribution network considering wind power uncertainty. The mode comprehensively considers the method of formulating the internal TOU price in the regional microgrid cluster system, the degree of response of each microgrid to price control measures, and the influence of the uncertain wind power on the TOU price scheme. Further, a multi-objective optimization problem of the transaction mode involving uncertain wind power is presented. The optimization maximizes the revenue of the microgrid operator while minimizing the total cost of electricity in the microgrid cluster system. In order to solve the optimization problem, an NSGA-II algorithm coupled with Monte Carlo is employed. Compared to the multi-objective particle swarm optimization algorithm, the presented algorithm can ensure the tractability of the constraints while avoiding the locally optimal issue. Experimental results verify the effectiveness of the presented method.

2. Regional microgrid cluster system

In the regional microgrid cluster system, the microgrid operator is not only the connecting hub of the regional multi-microgrid and the distribution network, but also the core of the regional microgrid cluster system. Specifically, if the wind power cannot be utilized inside the multi-microgrid, the operator stores the power into the energy storage system. For the case of low external TOU price, the operator purchases and stores the wind power. As a result, the strategy helps the distribution network to shift peak load, while assisting the multi-microgrid to meet more load demand during peak period. In addition, the strategy is able to improve the utilization of wind power, so that the total cost of electricity purchasing of microgrid can be further reduced.

The price differences between inside electricity transaction and outside electricity transaction result in the revenue of operator management regional microgrid cluster system. As the basic unit of regional microgrid cluster system, microgrids are equipped with wind power generators and energy storage system. Each microgrid in the region meets load demand with wind power generation and energy from electricity transaction. The transaction involves the trading of regional multi-microgrid and operator. The investment recovery period and construction process of the operator have been fully discussed in the research [10].

The main processes of internal energy trading in regional microgrid cluster system are as follows:

1) Operator integrates the load and wind power information of each microgrid in the region;
2) Comprehensive analyses of the energy storage situation and the TOU price of external grid is carried out for the operator;
3) Considering the impact of uncertain wind power on the TOU price scheme, the internal TOU price in the regional microgrid cluster is established;
4) Under the organization of the operator, microgrids in the region conduct transactions in the transaction centre, where each microgrid negotiates transaction power and settlement price according to their own wind power and load;
5) Once the operator and the microgrids agree on the unit price of the "transit fee", the operator, microgrids as buyers, and microgrids as sellers jointly sign a contract for the transaction.

3. Objective function and constraints

3.1. Objective function

Objective 1: maximizing the operating revenue of the operator. The income $obj_1$ of the regional microgrid cluster system operator is shown as Eq. (1) and Eq. (2).

$$obj_1 = \max (C_g + C_{mg} + C_{tr} - C_{ess})$$  \hspace{1cm} (1)
Objective 2: minimizing the regional microgrid cluster total electricity cost. The function expression of the regional microgrid cluster total electricity cost $obj_2$ is as follows:

$$obj_2 = \min(C_{mg} + C_{tr} - C_{mgess})$$

where $C_{mgess}$ is the storage and operation cost of the microgrid; $P_{mgch}$ and $P_{mgdch}$ are the microgrid charge and discharge power of the energy storage at time $t$. $P_{mgch}$ and $P_{mgdch}$ are the microgrid charge and discharge power of the energy storage at time $t$. $C_{mgess}$ is the energy storage investment and maintenance costs of operator; $c_{s,g}$ and $c_{b,g}$ are the electricity sale price and electricity purchase price of the distribution network at time $t$; $c_{s,mg}$ and $c_{b,mg}$ are the TOU price for the regional multi-microgrid to purchase electricity from the operator at time $t$; $c_{tr}$ is the “transit fee” paid by the regional microgrid cluster internal transaction; $C_{tr}$ is the energy storage investment and maintenance costs of operator; $m$ is the number of microgrid in the region; $c_{b,g}$ and $c_{s,g}$ are the electricity sale price and electricity purchase price of the distribution network at time $t$; $c_{s,mg}$ is the TOU price for the regional microgrid cluster to purchase electricity from the operator at time $t$; $c_{tr}$ is the “transit fee” paid by the regional microgrid cluster internal transaction; $c_{mgess}$ is the storage and operation cost of the microgrid; $P_{mgch}$ and $P_{mgdch}$ are the microgrid charge and discharge power of the energy storage at time $t$.

3.2. Constraints

The regional microgrid cluster system power balance constraint is shown as Eq. (5).

$$\begin{align*}
\sum_{t=1}^{T} P_{b,i,t} + \sum_{n=1}^{m} \sum_{t=1}^{T} P_{wind} &= \sum_{n=1}^{m} \sum_{t=1}^{T} P_{load} + \sum_{t=1}^{T} P_{s,i,t} \\
\sum_{n=1}^{m} \sum_{t=1}^{T} P_{b,mg,n,t} + \sum_{n=1}^{m} \sum_{t=1}^{T} P_{wind} &= \sum_{n=1}^{m} \sum_{t=1}^{T} P_{load} + \sum_{n=1}^{m} \sum_{t=1}^{T} P_{s,mg,n,t}
\end{align*}$$
where \( P_b \) is the power purchased by the operator; \( P_{\text{load}}^{\text{reg}} \) is the regional microgrid cluster system load demand; \( P_s \) is the power sold by the operator; \( P_{\text{b,mg}} \) is the multi-microgrid purchased power; \( P_{s,\text{mg}} \) is the power sold by multi-microgrid.

The uncertainty of wind power affects the economy of internal TOU price of the systems. Involving the uncertainty of wind power, the wind power constraints are shown as Eq. (6)[11].

\[
\begin{align*}
P_{\text{wind}}^{\text{n,t}} &= P_{\text{wind}}^{\text{n,\text{min}}} + \alpha_{n,t} (P_{\text{wind}}^{\text{n,\text{max}}} - P_{\text{wind}}^{\text{n,\text{min}}}), 0 \leq \alpha_{n,t} \leq 1 \\
\alpha_{n,t} &= \frac{\Delta t}{\beta_{n,t}} + \frac{P_{\text{width}}^{\text{n,\text{max}}}}{P_{\text{width}}^{\text{n,\text{min}}}} \\
P_{\text{wind}}^{\text{n,\text{max}}} &= P_{\text{pre,n,t}} + P_{\text{width}}^{\text{n,\text{max}}} \\
P_{\text{wind}}^{\text{n,\text{min}}} &\leq P_{\text{wind}}^{\text{n,t}} \leq P_{\text{wind}}^{\text{n,\text{max}}} \tag{6}
\end{align*}
\]

At time \( t \), \( P_{\text{wind}}^{\text{n,t}} \) is the value of the wind power; \( P_{\text{wind}}^{\text{n,\text{min}}} \) and \( P_{\text{wind}}^{\text{n,\text{max}}} \) are the minimum and maximum values of the wind power of microgrid \( n \); \( P_{\text{pre,n,t}} \) is the predicted value of the wind power of microgrid \( n \); \( P_{\text{width,n,t}} \) is the maximum fluctuation ranges of the wind power of microgrid \( n \); \( \alpha_{n,t} \) is the adjustable parameter of the wind power of microgrid \( n \); \( \beta_{n,t} \) is the value of the random variable of microgrid \( n \).

The energy storage power and state of charge constraints are shown as Eq. (7).

\[
\begin{align*}
\delta_{z,\text{soc,\text{min}}} \leq z_{\text{soc}} &\leq \delta_{z,\text{soc,max}} \\
\delta_{z,\text{soc,\text{min}}} + \frac{\eta_{\text{ess}} P_{\text{ch}} \Delta t}{U_{\text{bat}}} - \frac{P_{\text{dch}} \Delta t}{\eta_{\text{ess}} U_{\text{bat}}} &\leq z_{\text{soc}} \\
\Delta t &\leq P_{\text{ess,t}} \\
0 &\leq P_{\text{ch}} \leq P_{\text{max,\text{ch}}} \\
0 &\leq P_{\text{dch}} \leq P_{\text{max,\text{dch}}} \\
\end{align*}
\]

where \( \delta_{z,\text{soc,\text{min}}} \) and \( \delta_{z,\text{soc,max}} \) are the minimum and maximum values of the state of charge; \( \eta_{\text{ess}} \) is the energy storage conversion efficiency; \( U_{\text{bat}} \) is the energy storage capacity; \( \Delta t \) is the time step; \( P_{\text{ess,t}} \) is the energy storage capacity at time \( t \); \( P_{\text{max,\text{ch}}} \) and \( P_{\text{max,\text{dch}}} \) are the maximum charge and discharge powers of energy storage.

Detailed constraints of load translation are referred to the researches [12-13].

4. Optimization algorithm

The model is solved by NSGA-II. The specific steps of the algorithm are listed as follows:

**Step 1**: Generate the initial parent population \( P_p \).

**Step 2**: Use Monte Carlo method to generate \( M \) random wind power scenarios. Calculate \( obj_1 \) and \( obj_2 \) of the parent population \( P_p \) in different scenarios. Carry out the fast non-dominated sorting and the individual crowding calculation for the population \( P_p \).

**Step 3**: Select, crossover, mutate, so that the progeny population \( P_o \) is generated.

**Step 4**: Combine the populations \( P_p \) and \( P_o \) and generate the population \( P_r \). Then, Monte Carlo method generates \( M \) random wind power scenarios. Further, calculate \( obj_1 \) and \( obj_2 \) of the population \( P_r \) in different scenarios. Carry out the fast non-dominated sorting and congestion calculation for the population \( P_r \).

**Step 5**: Using the elite retention strategy, select outstanding individuals to form a new parent population \( P_{r+1} \).
Step 6: If the termination condition is satisfied while the Pareto front is obtained, algorithm terminates; otherwise, repeat the loop steps (3) - (5).

5. Case studies

5.1. Parameters

Based on a regional microgrid cluster system consisting of three microgrids, the experiments are performed. For the three microgrids, the capacities of the wind power generators are 5MW, 4MW, and 3MW; the rated capacities of energy storage systems are 1000 kW, 800 kW, and 500 kW. The rated energy storage capacity of the operator is 4000 kW. The wind power and load prediction curves for typical days of each microgrid (non-real grid data) are shown in Appendix Figure A1. The parameters of energy storage are shown in Appendix Table A1. The TOU price of distribution network is detailed in the researches [11].

5.2. Experimental results

The basic parameters of the NSGA-II algorithm are configured as follows: population evolution time is 1000; population size is 100; individual crossover probability is 0.8; individual mutate probability is 0.1; random wind power scenarios generated by the Monte Carlo method is 100 per iteration.

The Pareto solution set considering uncertainty consists of two parts: 1) the average cost of the regional microgrid cluster in 100 random scenarios; 2) the average revenue of the operator in 100 random scenarios. TOU price is set by the operator. Therefore, under the condition that the total electricity cost of microgrid cluster is greatly reduced, the solution with the largest revenue of regional microgrid cluster operator is selected as an ideal compromise solution.

Table 1. Comparison of electricity costs under different operation modes.

|                         | Peak period price (CNY/kW·h) | Flat period price (CNY/kW·h) | Valley period price (CNY/kW·h) | Total cost (CNY) |
|-------------------------|-----------------------------|-----------------------------|-------------------------------|-----------------|
| Regional microgrid      | 1.5611                      | 0.9000                      | 0.6783                        | 10597           |
| cluster system          |                             |                             |                               |                 |
| Decentralized           | 1.3500                      | 0.9000                      | 0.5000                        | 15608           |
| microgrids              |                             |                             |                               |                 |

Table 1 compares the total electricity costs of the compromise solution and decentralized microgrids. As show in the table, although the electricity prices of the peak and valley periods of the presented mode are higher than that of decentralized microgrids, the total electricity cost of regional microgrid cluster is greatly reduced. Therefore, compared to the decentralized microgrids, the presented mode can reduce the total electricity cost for each microgrid.

![Figure 1. MG1-3 Power shortage curve before and after load translation.](image-url)
The load shifting of each microgrid based on the internal and external TOU price scheme is shown in Figure 1. The figure indicates that during the peak periods, the internal TOU price lead to more load shifting for each microgrid. However, the load shifting amount is less during the flat periods. Both the points are attributed to the presented mode, which can set internal TOU price based on the electricity consumption in the region. Ultimately, the internal price considering the electricity consumption can guide the microgrids to carry out suitable “peak load shifting”.

Figure 2 shows the energy interaction between the regional microgrid cluster system and the distribution network. The figure illustrates that the peaks of exchanged energy reach -2.66 MWh and 2.62 MWh in the case of decentralized microgrids. Meanwhile, it can be clearly seen that the decentralized microgrids totally purchase 25.99 MWh electricity and sell 25.45 MWh electricity. Both the two points imply the frequent energy interaction of decentralized mode, which adversely affects the operation of the distribution network and increase the cost of electricity for each microgrid.

Figure 2 also shows the energy interaction curve between regional microgrid cluster system and distribution network. It can be clearly seen that both the peak transaction and total transaction decrease significantly. The decreased transaction not only alleviates the operating pressure of distribution network in peak period, but also greatly improves the overall economy for microgrids.

In order to demonstrate the effectiveness of TOU pricing scheme considering wind power uncertainty, NSGA-II algorithm is applied to solve the deterministic pricing scheme. And then, 1000 random real-time scenarios are generated by Monte Carlo method. Finally, the economy of the scheme considering uncertainty is compared to that of a scheme without consideration of uncertainty.
The distribution of each scenario of two schemes are shown in Figure 3 and Figure 4. As shown in the Figure 3, total electricity cost of the scheme considering uncertain wind power is generally lower than that of the deterministic scheme. In addition, Figure 4 further indicates that the revenue of operator is higher than that of the deterministic scheme.

| Table 2. Comparison of electricity price, cost, and income under different schemes. |
|-----------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
|                                  | Peak periods price (CNY/ kWh)   | Flat periods price (CNY/ kWh)   | Valley periods price (CNY/ kWh) | Total electricity cost (CNY)   | Total revenue (CNY)             |
| Deterministic scheme             | 1.5692                          | 0.9000                          | 0.6264                          | 11062                          | 4550.0                          |
| Uncertainty scheme               | 1.5611                          | 0.9000                          | 0.6783                          | 10798                          | 5243.9                          |

The average of all the scenarios of the two schemes are further shown in Table 2. It can be seen clearly that although the valley periods considering the uncertainty is higher than that of the deterministic scheme, the total electricity cost of the scheme involving uncertainty is lower than that of the deterministic scheme. Meanwhile, compared to the deterministic scheme, the scheme considering uncertainty leads to significant improvement in terms of operator revenue.

6. Conclusions
This paper presents an energy transaction mode of regional microgrid cluster and distribution network considering wind power uncertainty, in which a TOU price multi-objective optimization problem is modelled. Further, the NSGA-II algorithm combined with Monte Carlo method is employed to solve the optimization problem. Finally, based on the experiment, the effectiveness of the mode is demonstrated as follows:
1) The internal TOU price of the regional microgrid cluster system can effectively coordinate the microgrid to perform load shifting according to the overall situation of the system, and assist the distribution network to perform “peak load shifting”.
2) Considering the uncertainty of wind power, the TOU price scheme can increase revenue of the operator while reducing the total cost of regional microgrid cluster.
3) Based on the coordination between the energy storage system and optimized TOU price, the presented mode greatly improves the wind power utilization of microgrids. Ultimately, the unnecessary energy interaction between the microgrid and the distribution network is significantly reduced.

Above all, it can be concluded that the presented mode fully utilizes wind power resources to reduce the electricity cost of microgrids. In addition, the adjustment of internal TOU price and large-capacity energy storage system is able to alleviate the operating pressure of distribution network.

Acknowledgement
The paper is supported by the project of the State Grid Sichuan Economic Research Institute.

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Appendix

Figure A1. MG1-3 typical daily wind power and load prediction curve.

Table A1. Parameters of operator and microgrid 1-3 ESS unit.

|                        | Microgrid 1 | Microgrid 2 | Microgrid 3 | Operator |
|------------------------|-------------|-------------|-------------|----------|
| Rated capacities / (kW)| 1000        | 800         | 500         | 4000     |
| Maximum charge and discharge power / (kW) | 500 | 400 | 250 | 1200 |
| Maximum remaining battery level / (%) | 90 | 90 | 90 | 90 |
| Minimum remaining battery level / (%) | 20 | 20 | 20 | 90 |
| Initial quantity of electricity / (%) | 20 | 20 | 20 | 20 |
| Operation and maintenance costs / (CNY/kW·h) | 0.05 | 0.05 | 0.05 | 0.05 |