The optimal allocation of dispatchable resources considering the flexibility of microgrid

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Abstract. In order to improve the ability of the microgrid to deal with uncertain interference and flexibly adapt to the frequent variability and strong uncertainty of renewable energy that is connected in high proportion, a method increasing the flexibility of the microgrid is proposed through the capacity configuration of power units of multiple types as well as the participation and response of demand side. From the point of view of supply and demand balance, the flexibility of microgrid is analyzed quantitatively. The particle swarm optimization algorithm is used to optimize the capacity configuration of the system, and the optimal dispatching model with the lowest operating cost and the maximum flexibility margin of the system is established with the capacity of multiple types of units and load response capacity as decision variables. The example analysis shows that this method can greatly improve the overall flexibility of the microgrid while ensuring that the system investment and operating costs are relatively small.

1. Introduction
With the change of environment and the consumption of primary energy, renewable energy presents a blowout development. As one of the ways to utilize renewable energy efficiently, micro-grid has great development potential. However, for independent MEGAwatt (MW) microgrid, without the support of the superior power grid, the fluctuating load is often limited by the climbing capacity of the generating set, and the intermittent feature of the renewable energy connected with a high proportion also affects the power supply reliability of the whole system. Therefore, it is necessary to study how to improve the adaptability and flexibility of microgrids from both qualitative and quantitative aspects. Literature [1-2] introduces the characteristics and specific concepts of the flexibility of power system, and points out that the key to the flexibility of the system lies in the establishment of the flexibility index. Literature [3-4] coordinates the output of multi-type power units and optimizes the allocation of limited flexibility resources on the generation side, however does not take into account the self-regulation effect on the demand side. In general, flexibility is an important evaluation index to consider the stable operation of microgrids in the future. In order to improve the flexibility and economy of micro grid, this paper firstly quantifies the flexibility margin index of micro grid reasonably. Then an independent optimal configuration model is established to optimize the adjustment and compensation of the potential load and energy storage sides globally. Finally, the superiority of the proposed model is verified by an IPSO algorithm with an example of an independent micro-network programming.
2. Flexibility of microgrids

2.1. Definition of flexibility margin of microgrid
The flexibility of micro-grid refers to the ability of the system to allocate various types of flexible resources to adapt to load curve changes and uncontrollable fluctuations of renewable energy[5]. Improving the flexibility of micro-grid can effectively reduce the negative impact brought by the double uncertainties of the generation side and the load side. Load and wind power output can fluctuate up and down, indicating that flexibility is also directional, that is, up flexibility and down flexibility. This paper analyzes the supply of flexibility to the system one by one from the three aspects of power side unit configuration, demand side load response and energy storage device configuration.

2.2. Power side flexibility resource
In the micro-grid, in addition to the access to a large amount of renewable energy represented by wind power, a relatively large amount of controllable distributed energy is also required, mainly including diesel generator(DEG), micro gas turbine(MT) and fuel cell(FC). The complementary characteristics of wind power and three types of controllable distributed energy are utilized to mitigate the adverse effects of wind power access into the system. For the rise or fall of net load that may occur in the next period, the controllable unit on the power side can effectively carry out flexible upward/downward adjustment.

\[ S_{u_{\Omega,t}} = \sum_{i=1}^{1} \min (P_{i,\max} - P_{i,t}, R_{i}^{\text{up}} \cdot \Delta t) \]

\[ S_{d_{\Omega,t}} = \sum_{i=1}^{1} \min (P_{i,t} - P_{i,\min}, R_{i}^{\text{down}} \cdot \Delta t) \]

In the type, \( S_{u_{\Omega,t}} \), \( S_{d_{\Omega,t}} \) is respectively the up-regulated flexibility margin and down-regulated flexibility margin available for each power unit on the generating side at time \( t \); When \( i=1,2,3 \), \( P_{i,\max} \) and \( P_{i,\min} \) are respectively the upper and lower limits of technical output of DEG, MT and FC in the system, \( P_{i,t} \) are respectively the actual output of DEG, MT and FC at time \( t \), \( R_{i}^{\text{up}} \) and \( R_{i}^{\text{down}} \) are respectively the upward climbing rate and downward climbing rate of DEG, MT and FC. \( \Delta t \) is scheduling interval.

2.3. Load side flexibility resources
The demand response participates in the optimal configuration of the micro grid, plays the role of load peak-shaving, and provides the system with up-regulation flexibility capacity. In this paper, an incentive demand response model is adopted to build a master-slave game model of single demand response supplier (DRPs) and multiple users participating in demand response. DRPs, as an intermediary agent of microgrid, makes scheduling plans and arranges various adjustable flexible loads and interruptible loads to participate in the scheduling of microgrid. The scheduling cost of the demand response adopts a tiered compensation mechanism, as shown in Figure 1.
In the type, \( C_{\text{curt}} \) represents the load compensation expense, \( Q_1, Q_2, \ldots, Q_k \) is the load compensation expense of each level, \( P_{LF,t} \) is the adjustment quantity of demand response at time \( t \), \( kP_c \) is the capacity of the level \( k \) load compensation.

### 2.4. Energy storing device

The energy storage device uses battery, as a special kind of flexible resource, which can transfer the limited energy stored into the system, and also can store the surplus energy in the system, that is, it has adjustable capacity up and adjustable capacity down:

\[
S_{\text{store},t}^u = \sum_{m=1}^{M} \min((S_{\text{SOC},t+1}^m - S_{\text{SOC},t}^m)S_{\text{BD},t}^{\text{max}})\eta_c \tag{4}
\]
\[
S_{\text{store},t}^d = \sum_{m=1}^{M} \min((S_{\text{SOC},t+1}^m - S_{\text{SOC},t}^m)S_{\text{BD},t}^{\text{max}})\eta_g \tag{5}
\]

In the type, \( M \) is the total number of battery configurations in the system, \( S_{\text{SOC},t+1}^m \) represents the charged state of the \( M \) battery at time \( t-1 \), \( P_{\text{BD},t}^{\text{max}} \), \( S_{\text{BD},t} \) is the rated power and capacity of the battery respectively, \( \eta_c, \eta_g \) is the discharge and charging efficiency of the battery respectively, \( S_{\text{SOC},t}^{\text{max}}, S_{\text{SOC},t}^{\text{min}} \) is respectively the maximum and minimum charged state of the battery, and its value affects the service life of the battery. In this paper, the energy storage device implements the operation characteristic of "multiple charge and two discharge", charging at the low load at night or when the wind power output is surplus in the day, and discharging at the noon peak time and evening peak time.

### 3. Flexibility capacity requirement analysis

The flexible capacity demand of micro-grid is derived from the uncertainty of wind power output and load forecast, and the capacity demand of the system for the fluctuation of wind power output and load at the next moment, as shown in Equation (6):

\[
P_{\text{Fr},t} = (P_{L,t+1} - P_{L,t}) - (P_{W,t+1} - P_{W,t}) + (N_{L,t+1} - N_{L,t}) + \lambda_{e,t+1} + \lambda_{e,t+1} \tag{6}
\]

In the type, \( P_{\text{Fr},t} \) is the flexible demand capacity of the system from time period \( T \) to the next scheduling interval. \( N_{L,t+1}, N_{W,t+1} \) is respectively the demand of load and wind power output for regulating capacity due to prediction error in time period \( t+1 \). \( P_{L,t}, P_{W,t} \) is respectively the predicted value of load and wind power output in time period \( t \). \( \lambda_{e,t+1} \) is the capacity demand of the system during the time period \( t+1 \).
4. Mathematical model

4.1. Objective function

4.1.1. Flexibility margin indicator objective function
Equations (7) and (8) are reasonably quantified up/down flexibility margin indicators. The planning cycle of micro grid system includes typical scenes of four seasons, spring, summer, autumn and winter.

$$\max F_1 = \frac{1}{S} \sum_{s=1}^{S} \left( S^{\text{store,u}} + (\alpha P_{\text{L,s}} - P_{\text{FC,s}}) + S^{\text{store,u}} \right)$$

In the type, S is the total number of scenes, and 1/S is the probability of each scene. \(\tau_s\) is the peak period of in day net load in the s scene, \(\alpha\) is the maximum response depth on the demand side. The physical meaning of the objective function is the ratio of supply and demand capacity of the system in the peak period of net load approaching.

$$\max F_2 = \frac{\sum_{s=1}^{S} \sum_{t=1}^{T} (P_{\text{W},t} - N_{\text{W},t})}{\sum_{s=1}^{S} \sum_{t=1}^{T} P_{\text{W},t}}$$

In the type, \(N_{\text{W},t}\) is the wind abandoning power of the system at time \(t\).

4.1.2. Optimize the allocation of economic cost objective function
As shown in the following formula, the cost objective function mainly considers the capacity allocation cost, fuel cost, environmental pollution penalty cost, wind abandon penalty cost and demand response compensation cost of each power unit.

$$\min F_3 = C_T + C_{\text{curt}} + C_{\text{oper}} + C_{\text{envi}} + C_{\text{res}}$$

In the type, \(C_T\) represents the capacity configuration cost of each generator set, \(C_{\text{curt}}\) represents the compensation cost of demand side response, \(C_{\text{oper}}\) represents the operating cost of each generator set, and \(C_{\text{res}}\) represents the penalty cost of abandoning wind. \(C_{\text{MD}}, C_{\text{MT}}, C_{\text{FC}}\) respectively, MT , DEG generator unit, the unit of FC capacity allocation cost (including unit costs, installation costs, maintenance costs), \(Q_{\text{MD}}, Q_{\text{MT}}, Q_{\text{FC}}\) respectively, MT , DEG generator units, FC the configuration of the total capacity, \(Na\) means the life of the distributed power supply unit, 13a, \(r\) is expressed as the actual lending rates, 6.7%; \(K_{\text{MD}}, K_{\text{MT}}, K_{\text{FC}}\) respectively represent the fuel cost per unit generating capacity of DEG generator sets, MT generator sets, and FC; \(V_{\text{MD}}, V_{\text{MT}}, V_{\text{FC}}\) are respectively the penalty cost of NO\textsubscript{X}, CO\textsubscript{2}, CO and SO\textsubscript{2} pollution discharged by DEG generator set, MT generator set and FC per unit of generating capacity.

4.2. Constraint condition
1) Power balance constraint
\begin{equation}
\sum_{i=1}^{1} P_{L,t} + P_{W,t} + \sum_{m=1}^{M} P_{m_{SR},t} - N_{W,t} = P_{L,t} - P_{L,F,t}
\end{equation}

In the type, $P_{m_{SR},t}$ is the output of the $m$ battery, and the energy storage is in the positive direction when discharging.

2) Adjustable flexible load constraint

\begin{equation}
0 \leq P_{L,t} \leq \alpha P_{L,t}
\end{equation}

3) Unit output and climbing constraints

\begin{equation}
0 \leq P_{L,t} \leq \alpha P_{L,t}
\end{equation}

\begin{equation}
\left\{ P_{L,t} + \Delta t - P_{L,t} \leq R_{m} \Delta t \quad P_{L,t} + \Delta t - P_{L,t} \geq 0 \right\}
\end{equation}

\begin{equation}
P_{L,t} + \Delta t - P_{L,t} \leq R_{\alpha_{m}} \Delta t \quad P_{L,t} + \Delta t - P_{L,t} < 0
\end{equation}

4) Energy storage charged state and output upper and lower limits constraints

\begin{equation}
S_{SOC_{min}} \leq S_{SOC_{F,t}} \leq S_{SOC_{max}}
\end{equation}

5. Analysis of examples

5.1 Data analysis

In the simulation, the wind power generation and load data adopted the prediction data of a certain place in north China. The load and wind power output prediction curves of typical scenes in spring, summer, autumn and winter of the micro-grid system are shown in Figure 2 and Figure 3, and the sampling interval is 1h.

5.2 Multi-objective population solution

In practical programming, multi-objective particle swarm optimization algorithm is used to solve the model, and an optimal configuration scheme is selected from Pareto optimal solution set[6]. Fuzzy entropy weight method was used to determine the weights of index and cost-type objective functions[7-8], and the pros and cons of each objective function were obtained according to the subjective fuzzy satisfaction degree of decision maker and the objective entropy weight information of Pareto solution set. A fuzzy membership function with weighted values is constructed, as shown in the following formula, Pareto solution is sorted, and the global optimal solution is finally obtained.

\begin{equation}
L = \sum_{i=1}^{3} \lambda_{i} H_{i} = \begin{cases} 
0 
& F_{i} \leq F_{i}^{min} \\
\lambda_{i} \frac{F_{i}^{max} - F_{i}^{min}}{F_{i}^{max} - F_{i}^{min}} 
& F_{i}^{min} < F_{i} < F_{i}^{max} \\
\lambda_{i} 
& F_{i} \geq F_{i}^{max}
\end{cases}
\end{equation}
In the type, $F_i^{\min}$, $F_i^{\max}$ respectively represents the upper and lower limit value of Pareto solution for the ith target, while $i$ is the weight value of the ith target.

5.3 Simulated analysis

5.3.1 Scene Settings

Case 1: Microgrids only consider all kinds of distributed power sources (DEG, MT, FC) as flexible resources to optimize capacity allocation.

Case 2: Micro grid considers all kinds of distributed power sources (DEG, MT, FC) and SB as flexible resources to optimize capacity allocation.

Case 3: On the basis of Case 2, demand response resources are considered to participate in virtual capacity optimization configuration.

Table 1 shows the allocation results of various flexible resource capacities and the indexes of economic cost and flexibility margin after optimization of the three schemes.

| Device type | Case 1 configuration results | Case 2 configuration results | Case 3 configuration results |
|-------------|-----------------------------|-----------------------------|-----------------------------|
|             | (set)                       | (set)                       | (set)                       |
| DEG         | 48 / 51                     | 48                          | 48                          |
| MT          | 11 / 30                     | 9                           | 7                           |
| FC          | 0 / 24                      | 0                           | 0                           |
| SB          | /                           | 63                          | 80                          |
| Investment operation cost($) | 3923                        | 3865                        | 3695                        |
| Up/down flexibility margin indicator | 1.56/0.82                  | 1.56/0.82                  | 1.59/0.89                  |

5.3.2 Analysis of the influence of complementary characteristics of DEG and MT on the system

By comparing the different configuration results of the four cases in Case 1, it is easy to conclude that the complementary characteristics of DEG and MT generator sets greatly improve the economy and flexibility of the system. DEG generating sets have a high configuration cost, while MT generating sets have a low fuel cost. According to the results of optimal configuration, complementary generation of DEG and MT generating sets has a positive impact on the economic benefits of the system.

5.3.3 Analysis of the impact of energy storage and demand response on system flexibility

Figure 4, Figure 5 and Figure 6 respectively show the optimal output curves of distributed power supply and energy storage on a typical day in summer for each case, as well as the demand response curves. Compared with Case 1 (considering DEG, MT and FC), energy storage is considered as a flexibility resource in Case 2, which mainly improves the flexibility downregulation space and reduces the penalty cost of wind abandoning power. The investment operation cost decreased from 3923$ in Case 1 to 3865$ in Case 2, the flexibility margin index increased from 1.56 to 1.59, and the flexibility margin index increased from 0.82 to 0.89, with an increase ratio of 8.54%.

Case 3 considers the demand response resource as the flexibility resource, which mainly improves the flexibility up-regulation space and reduces the operating cost and configuration cost of the generator set. Case 3 DEG in generator sets than Case 2 reduce four, MT generator to reduce 2 sets, investment operation cost decreased from 3,865$ of Case 2 to 3,695$ of Case 3, with a decrease rate of
4.4%, the improved flexibility margin index was raised from 1.59 to 1.73, with an increase ratio of 8.81%, and the down flexibility margin index was raised from 0.89 to 0.91, with an increase ratio of 2.25%. Thus, it can be concluded that the participation of energy storage and demand response resources in the capacity optimization allocation of independent micro grid plays a positive role in improving the quantitative index of flexibility margin and economy proposed in this paper.

6. Conclusion

- This paper presents a coordinated and optimized scheduling method for multiple source complementation and demand response. The flexibility of the micro grid is greatly improved to better deal with the uncertainty in each period while ensuring the economy of the system.
- In this paper, the demand response is taken as a flexible resource to improve the adjustable capacity by compensating the load at a low cost, and the operation strategy of each dispatching layer of the source network and storage is planned as a whole, so that the economic benefit and flexibility margin index benefit of the micro-grid system can be maximized, which plays a positive guiding role for the independent micro-grid in the configuration planning.

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