Research on capacity configuration and operation scheduling optimization of multi-energy complementary microgrid

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Abstract. Based on the introduction of the structure of the multi-energy complementary microgrid system, aiming at the multi-objective optimization problems of the operational economy and the contact line power volatility, the corresponding objective functions and constraints are given, and the model for capacity configuration and operation scheduling optimization of the multi-energy complementary microgrid system is established. The improved particle swarm optimization method is used to solve the problem. The calculation results of the example verify the feasibility and effectiveness of the proposed optimization model and its optimization algorithm.

1. Introduction

In recent years, distributed generation technologies have gained importance and development in the world. Relative to centralized power supplies, distributed power supplies have the advantages of environmental protection, low investment, short construction period, and near power supply [1,2]. However, due to the randomness and volatility of the output of distributed power sources such as wind turbine and photovoltaic, they will have a certain impact on the stable operation of the large power grid system when they are connected to the power grid on a large scale [3,4]. In this context, the concept of a multi-energy complementary microgrid proposes a new feasible direction for the use of distributed power [5].

At present, a great deal of research has been conducted on the optimal configuration of multi-energy complementary microgrid. The main research directions are energy-saving and economicality, equipment and materials for equipment, optimization of operations, load matching and control strategies, modeling and performance simulation of multi-energy complementary microgrid. For the optimal configuration of systems with multi-energy complementary microgrid, Beihong and Weiding used a hybrid integer nonlinear model to optimize the power plant's co-provisioned system configuration [6]. Xu [7] introduces conditional risk value theory and confidence method to describe the uncertainty of virtual power plant operation (VPP), maximizes the operating profit as the objective function, establishes the VPP general dispatching optimization model, and determines the threshold of VPP operating income. Aiming at the goal of optimizing the economics of the combined cold heat and power supply system, Kong establishes a model to optimize the system equipment configuration [8]. Yokoyama optimizes the equipment configuration and operation strategy of the gas turbine cogeneration system [9]. Xu [10] jumped out of the scope of power system and summarized the
matching problem of energy production and consumption at the aspect of electric thermal joint system. An electric-heat combined system that includes large-capacity heat storage can take full advantage of the physical characteristics of the power system and thermal system, and improve the ability of the energy system to optimize the configuration over a large space-time range. Lu [11] proposed a method of wind energy hybrid energy storage capacity allocation based on wavelet packet decomposition. In this method, the output power of wind turbine is decomposed by wavelet packet, and it is decomposed into low frequency part and high frequency part, and the low frequency part is used as the target power of grid connection. According to the complementary characteristics of the battery and the super capacitor, they are used to suppress the high frequency part and the high frequency part, respectively. Chen [12] proposes to develop gas storage technology in the microgrid, converts the surplus wind power into natural gas for storage through electric gas conversion technology, and reduces the phenomena of abandoning wind and abandoning light.

This paper establishes a multi-objective capacity configuration and operation scheduling optimization model based on the total cost of microgrid system and contact line power volatility. Taking the load data of a multi-energy complementary microgrid system in a certain country as an example, the model proposed in this paper is verified and analyzed by using an improved particle swarm algorithm.

2. Multi-energy complementary microgrid system structure
The multi-energy complementary microgrid is a self-contained unit with independent energy supply and collaborative grid power supply capability. For a multi-energy complementary microgrid system, its typical components include three parts: a distributed generation system, a distributed energy storage system, and a combined cold heat and power supply system. The multi-energy complementary microgrid system has heat, cold, and electric energy flow, and the energy is exchanged and coupled through electricity, cold, and heat buses to provide energy transmission channels for the combined cold heat and power supply system. The structure diagram of the multi-energy complementary microgrid system studied in this paper is shown in figure 1.

![Diagram of Multi-energy Complementary Microgrid System](image)

**Figure 1.** Multi-energy complementary microgrid system structure diagram.

3. Capacity configuration optimization of multi-energy complementary microgrid
The optimization objectives are usually considered in the capacity configuration and operation
scheduling optimization of the multi-energy complementary microgrid system include two aspects: operation economy and contact line power volatility. Under normal circumstances, the operation economy and contact line power volatility cannot be optimal at the same time. Therefore, the optimization calculation of the multi-energy complementary microgrid system is actually a compromise between the two.

This paper aims at the multi-objective optimization of multi-energy complementary microgrid system operation economy and contact line power volatility. Combining with the complexity of the problem and the form of optimal solution, it uses the weighted method based on the linear weighted idea to perform single-objective processing on multi-objective problems [13].

3.1. Objective function

In the process of building the multi-energy complementary microgrid capacity configuration and operation scheduling optimization model, the objective function includes two parts: the minimum economic cost and the lowest volatility of the contact line power. This article uses linear weighting to perform single-targeted processing on the double-target problem.

3.1.1. Economic cost. This paper mainly considers its annual installed costs, operating costs, and maintenance costs when discussing the minimization of its economic cost \( C_{yx} \). Its function expression is

\[
C_{yx} = f_{ins} + f_{run} + f_{main}
\]  

(1)

where \( f_{ins} \) is the annualized installed costs; \( f_{run} \) is the annualized operating costs and \( f_{main} \) annualized maintenance costs.

Assuming that the system planning period is \( n \) years and the battery life is \( n_{se} \) years, the installed costs of the multi-energy complementary microgrid system is averagely converted to the year, and the annualized installation costs \( f_{ins} \) is

\[
f_{ins} = \frac{r(1+r)^n}{(1+r)^n-1} \left( T_u C_{sa} + T_{hec} C_{hse} + T_{gt} C_{g} + T_{hr} C_{hr} + T_{hg} C_{hg} \right) + \frac{r(1+r)^{n_{se}}}{(1+r)^{n_{se}}-1} T_u C_{se}
\]  

(2)

where \( r \) is the discount rate, estimated at 9%; \( C_{sa} \) is the cost of installed cooling energy storage equipment, which is 400,000 yuan; \( C_{hse} \) is the installed cost of heating energy storage equipment, which is 50,000 yuan; \( C_{g} \) is the installed cost of gas turbines, which is 200,000 yuan; \( C_{hr} \) is the installed cost of heat recovery boilers, which is 12,500 yuan; \( C_{hg} \) is the installed cost of gas boilers, which is 60,000 yuan; \( C_{se} \) is the cost of installed electric energy storage equipment, which is 500,000 yuan; \( T_u, T_{hec}, T_{gr}, T_{hr}, T_{hg}, T_{se} \) is the number of distributed device.

The operating costs of the multi-energy complementary microgrid system include the cost of natural gas consumed \( f_{gas} \) and the cost of purchasing electricity from the grid \( f_{grid} \). Annualized operating cost \( f_{run} \) expression is

\[
\begin{align*}
 f_{run} & = f_{gas} + f_{grid} \\
 f_{gas} & = P_{gas} \frac{P_{gt}(t)}{\eta_{gt} HV_{gas}} \\
 f_{grid} & = \sum p_{grid}(t) P_{grid}(t)
\end{align*}
\]  

(3)

where \( p_{gas} \) is the price of natural gas, which is 2.8 yuan/m³; \( P_{gt}(t) \) is the gas turbine output; \( \eta_{gt} \) is gas turbine power generation efficiency; \( HV_{gas} \) is the natural gas thermal value, which is 9.879 kWh/m³; \( p_{grid} \) is the grid time-of-use price; \( P_{grid}(t) \) is the electricity purchase from the grid.

The annualized maintenance cost \( f_{main} \) function expression is
\[ f_{\text{main}} = T_w W_{w_e} + T_{w_e} W_{w_e} + T_{w_e} W_{w_e} + T_{w_e} W_{w_e} + T_{w_e} W_{w_e} + T_{w_e} W_{w_e} \]  

(4)

where \( W_{w_e}, W_{w_e}, W_{w_e}, W_{w_e}, W_{w_e}, W_{w_e} \) is the maintenance cost of each component in the system.

3.1.2. Service life of battery. Since the life of different battery are different, when calculating the economic costs of battery, the investment costs of battery need to be converted into annual values.

The service life of battery is closely related to the working mode, and is mainly affected by the depth of discharge (DOD) of the battery and the number of cycles used. The greater the depth of discharge of battery is, the shorter the service life is. The DOD of the battery is the percentage of the system's discharge magnitude and its nominal capacity. According to the corresponding relationship between the DOD of the battery and the service life of the energy storage cycle, the functional relationship can be fitted [14]. The statistical calculation of the DOD of the battery can adopt the rain flow counting method [15].

\[ N_B(D_i) = N_B(D_b) \left( \frac{D_i}{D_b} \right)^{0.19} e^{1.69(\frac{D_i}{D_b})} \]  

(5)

where \( D_b \) is the reference DOD of the battery, which is 0.6; \( N_B(D_i) \) is the corresponding battery life when the depth of discharge is \( D_i \). In this way, \( N_B(D_b) \) is the corresponding battery life when the depth of discharge is \( D_b \), estimated at 4,000 times. The cycle number when the depth of discharge \( D_i \) is the \( i \)th cycle corresponding to the DOD can be obtained.

\[ N(D_i) = \frac{N_B(D_i)}{N_B(D_b)} = \left( \frac{D_i}{D_b} \right)^{0.19} e^{1.69(\frac{D_i}{D_b} - 1)} \]  

(6)

The actual service life of the battery is

\[ n_w = \sum_{j=1}^{p} \sum_{l=1}^{I} N_j(D_i) \]  

(7)

where \( N_j(D_i) \) is the equivalent number of cycles corresponding to the \( i \)th cycle in the \( j \)th day; \( l \) is the number of charge and discharge times in 1d; \( p \) is the number of days of work operation in 1a.

3.1.3. Volatility rate of the contact line power. The volatility of the power of the contact line can, to a certain extent, reflect the influence of the microgrid on the large power grid. Therefore, it is necessary to analyze the volatility of the power of the contact line and obtain the power of the contact line that meets the requirements of the volatility. The evaluation indicator of the power volatility of the contact line is the volatility rate of the contact line power [16]. The volatility rate of the contact line power uses the standard deviation of the contact power to describe the volatility of the power of the contact line:

\[ \delta_{\text{grid}} = \sqrt{\frac{1}{T-1} \sum_{i=1}^{T} \left( P_{\text{grid},i} - P_{\text{grid,av}} \right)^2} \]  

(8)

where \( \delta_{\text{grid}} \) is the contact line volatility rate; \( P_{\text{grid,av}} \) is the contact line average power; \( P_{\text{grid},i} \) is the contact line power at the \( i \)th sampling point.

3.1.4. Total objective function. The total objective function is the sum of two objective functions.

\[ F_e = C_{y,x} + \lambda \sum_{i=1}^{T} \delta_{\text{grid}} \]  

(9)

where \( \lambda \) is the Weighting coefficient of \( \delta_{\text{grid}} \), which is 8,000.
3.2. Constraints

3.2.1. Balance constraints. Electric power balance constraint

\[ P_{\text{grid}} + P_{\text{gt}} + P_{\text{pv}} + P_{\text{wt}} = P_{\text{el}} + P_{\text{se}} + P_{\text{ec}} \]  

(10)

where \( P_{\text{grid}} \) is the purchases the electric power for the electrical network; \( P_{\text{gt}} \) is the gas turbine output power; \( P_{\text{pv}} \) is the photovoltaic output power; \( P_{\text{wt}} \) is the wind turbine output power; \( P_{\text{el}} \) is the electric load; \( P_{\text{se}} \) is the charge and discharge power of the electric energy storage equipment; \( P_{\text{ec}} \) is the electric chiller power.

Heat power balance constraint

\[ Q_{\text{hr}} + Q_{\text{hg}} = Q_{\text{hl}} + Q_{\text{hse}} \]  

(11)

where \( Q_{\text{hr}} \) is the heat power of the heat recovery boiler; \( Q_{\text{hg}} \) is the heat power of the gas boiler; \( Q_{\text{hl}} \) is the system heat load; \( Q_{\text{hse}} \) is the heat storage equipment heat power.

Cold power balance constraint

\[ Q_{\text{ec}} = Q_{\text{a}} + Q_{\text{sa}} \]  

(12)

where \( Q_{\text{ec}} \) is the cold power output of the electric chiller; \( Q_{\text{sa}} \) is the power of the cold storage equipment; \( Q_{\text{a}} \) is the system cold load.

3.2.2. Inequality constraints. Output/energy storage equipment power constraints

\[ K_i P_{i,\text{min}} \leq P_{\text{DG}} \leq K_i P_{i,\text{max}} \]  

(13)

where \( K_i \) is the status of the distributed equipment unit (1 indicates running, 0 indicates outage); \( P_{i,\text{min}}, P_{i,\text{max}} \) are power upper and lower limit values of each equipment unit; \( P_{\text{DG}} \) is the output power of the distributed equipment unit during the \( n \)th period.

Energy storage equipment energy storage constraints

\[ S_{i,\text{min}} \leq S_{i} \leq S_{i,\text{max}} \]  

(14)

where \( S_{i,\text{min}}, S_{i,\text{max}} \) are the energy storage energy upper and lower limit values of distributed energy storage equipment units; \( S_{i} \) is the energy storage value of distributed energy storage equipment units.

Microgrid system and grid system energy interaction constraint

\[ 0 \leq P_{\text{grid}} \leq P_{\text{grid,\text{max}}} \]  

(15)

where \( P_{\text{grid}} \) is the purchase power from the grid for the distributed energy-supply microgrid system; \( P_{\text{grid,\text{max}}}(500 \text{ kW}) \) is the upper limit for the energy interaction between the microgrid system and the grid system.

3.3. Optimization algorithm

In order to take into account both the convergence speed and the convergence accuracy of the optimization model algorithm for multi-energy complementary microgrid system capacity configuration and operation scheduling, an improved particle swarm optimization algorithm considering extreme value variation is used in this paper. In the early stage of searching, an improved particle swarm optimization algorithm with extreme variation was used to increase the ability of particles to jump out of local optimal traps. Global optimization was used to improve the convergence speed of the algorithm at the later stage of the algorithm.

The flow diagram of the extremal variation particle swarm algorithm is shown in figure 2.

This paper divides the energy optimization problem of a multi-energy complementary microgrid on a typical day into 24 time periods, and considers the output of 6 kinds of equipment such as se,
sa, gt, hse, hr, and ec as the one-dimensional particle in each time period. Then, the improved particle swarm algorithm was used to solve the problem.

![Flowchart](image_url)

**Figure 2.** Extremal variation particle swarm optimization flow chart.

### 4. Operation scheduling optimization of multi-energy complementary microgrid

According to the calculation method of the multi-energy complementary microgrid capacity configuration and operation scheduling optimization model above, the optimal configuration scheme of the system can be obtained, including the type, capacity, and corresponding number of devices. Under this optimal configuration, the optimal operation strategy of the multi-energy complementary microgrid can be sought to determine the operation scheduling plan of each equipment in the system.

#### 4.1. Objective function

When discussing the minimization of the operation scheduling cost of the multi-energy complementary microgrid system, the operating cost and maintenance cost are mainly considered, and the fixed investment cost of each equipment unit is considered as a sunk cost. Under the premise of guaranteeing the cold, heat and electric load demand, the objective function of pursuing the economy of multi-energy complementary microgrid systems is

\[
C_{yt} = \sum_{i \in D_g} \left[ K_{i,t} C_{\text{base}}(P_{i,t}) + K_{i,t} C_{\text{bat}}(P_{i,t}) + K_{i,t} (1 - K_{i,t})(C_{i,q,t}) \right] + \delta P_{\text{base},t} + K_{b,t} P_{b,t} M_{b,t} - K_{s,t} P_{s,t} M_{s,t} 
\]  

(16)

where \( C_{yt} \) is the cost of the \( t \)th period of the multi-energy complementary microgrid system; \( D_g \) is
the controllable output unit; $K_{i,t}$ the start and stop status of the micro power supply (0 means stop, 1 means start); $C_{oh,t}$ is the energy cost of the micro power supply; $P_{i,t}$ is the output power of the micro power supply; $C_{oh,c}$ is the operation and maintenance cost of the micro power supply; $C_{i,t}$ is the start-stop cost of the micro power supply equipment; $\delta P_{bat,t}$ is the battery charge and discharge penalty function; $K_{b,t}$, $K_{s,t}$ are the status of the purchase and sale of electricity from the grid by the microgrid (0 means no, 1 means yes); $P_{b,t}$, $P_{s,t}$ are the powers purchased and sold between the microgrid and the grid; $M_{b,t}$, $M_{s,t}$ are the prices of electricity purchased and sold by the microgrid to the grid.

The objective function of power volatility rate of the microgrid contact line power is the same as equation (8). The total objective function is the sum of two objective functions.

4.2. Constraints

$$F_{t} = \sum_{i=1}^{24} C_{yt,i} + \lambda \delta_{grid}$$

4.2.1. Balance constraints. Electric, heat, and cold power balance constraints are the same as the equations (11) and (12).

Energy conversion constraint

$$F_{gt} = \frac{P_{gt}}{\eta_{gt}} = \frac{Q_{bt}}{(1-\eta_{gt})\eta_{bt}}$$

where $F_{gt}$ is the natural gas heat consumed by the gas turbine; $\eta_{gt}$ is the efficiency of the heat recovery boiler.

4.2.2. Inequality constraints. Output and energy storage equipment power constraints and energy storage constraints of energy storage equipment are the same as equations (13) and (14).

Microgrid system and grid system energy interaction constraint

$$0 \leq P_{grid,t} \leq K_{b,t}P_{b,max}$$
$$0 \leq P_{grid,t} \leq K_{s,t}P_{s,max}$$
$$K_{b,t} + K_{s,t} \leq 1$$

where $P_{b,max}$, $P_{s,max}$ are the upper limit of the power of the multi-energy complementary microgrid system to purchase electricity from the grid and sell electricity to the grid; $P_{grid,t}$ are the power of multi-energy complementary microgrid systems to purchase electricity from the grid and sell electricity to the grid; $K_{b,t}$, $K_{s,t}$ are states of purchase or sale of electricity(0 means there is no electric power interaction, 1 means there is electric power interaction), and both are not 1.

Controllable output equipment with the shortest continuous operation time and the shortest continuous outage time constraint

$$\begin{align*}
(T_{i,\text{on},t}^{t-1} - MRT_{i})(K_{i,t-1} - K_{i,t}) & \geq 0 \\
(T_{i,\text{off},t}^{t-1} - MST_{i})(K_{i,t-1} - K_{i,t}) & \geq 0
\end{align*}$$

where $T_{i,\text{on},t}^{t-1}$, $T_{i,\text{off},t}^{t-1}$ are the continuous operation and outage time of the $i$-th controllable micro power supply at the time $t-1$; $MRT_{i}$, $MST_{i}$ are the minimum continuous operation and outage time of the $i$-th controllable micro power supply; $K_{i,t}$, $K_{i,t-1}$ are continuous operation and outage status of the controllable processing equipment.

Controllable output equipment power ramp rate constraint
\[
\begin{cases}
P_i - P_{i-1} \leq \Delta P_U \\
P_i - P_{i-1} \leq \Delta P_D
\end{cases}
\]  
(21)

where \( P_i, P_{i-1} \) for the controllable processing equipment output at different times; \( \Delta P_U \) is the rate of increase limit; \( \Delta P_D \) is the rate of decrease limit.

5. Analysis of examples

5.1. Load, environmental data and equipment parameters

This paper takes the load data of a multi-energy complementary system in a certain country as an example for verification analysis. Using the specific data such as load and equipment parameters given in this paper, the optimal operation of the multi-energy complementary microgrid system is solved, and the operation plan of each equipment in different days of the day is obtained. The objective function and related constraints are described in sections 3.1 and 3.2.

Light intensity as shown in figure 3. The wind speed is shown in figure 4. Relative humidity is shown in figure 5. The outdoor temperature is shown in figure 6. The typical daily real-time electricity price curve is shown in figure 7. The detailed typical cold, heat, and electric load curves are shown in figure 8. The typical daily PV and wind turbine output curves are shown in figure 9. The parameters of the distributed energy storage equipment unit are shown in table 1. The main parameters of combined supply system equipment are shown in tables 2 and 3.

![Light intensity curve](image1)

**Figure 3.** Light intensity curve.

![Wind speed curve](image2)

**Figure 4.** Wind speed curve.

![Relative humidity curve](image3)

**Figure 5.** Relative humidity curve.

![Outdoor temperature curve](image4)

**Figure 6.** Outdoor temperature curve.
Figure 7. Real-time electricity price curve.

Figure 8. Cold, heat and electric load curves.

Figure 9. Photovoltaic, wind turbine output curve.

Table 1. Distributed energy storage equipment unit parameters.

| Parameters                        | Energy storage equipment |               |               |               |
|-----------------------------------|--------------------------|---------------|---------------|---------------|
|                                   | Electric energy storage  | Cooling energy storage | Heating energy storage |
| Rated power (kWh)                 | 1000                     | 1000          | 1000          |
| Charge power limit (kW)           | 200                      | 200           | 200           |
| Discharge power limit (kW)        | 200                      | 200           | 200           |
| Operation and maintenance costs (yuan·kW⁻¹) | 0.27                     | 0.35          | 0.37          |

Table 2. Combined supply system active equipment main parameters.

| Parameters                        | Type of controllable equipment |               |               |
|-----------------------------------|---------------------------------|---------------|---------------|
|                                   | Gas turbine                     | Gas boiler    | Electric chiller |
| Rated efficiency                  | 37%                             | 86%           | COP=5         |
| Upper limit of power (kW)         | 600                             | 500           | 200           |
| Lower limit of power (kW)         | 200                             | 50            | 200           |
| Operation and maintenance costs (yuan·kW⁻¹) | 0.035                     | 0.037         | 0.37          |
| Startup costs (yuan)              | 3                               | 3             | 1             |
| Min continuous operating time (h) | 2                               | 2             | 1             |
Min continuous outage time (h) & 2 & 2 & 1 \\
Active output rise rate (kW·h⁻¹) & 1050 & 400 & 1000 \\
Active output decrease rate (kW·h⁻¹) & 1300 & 700 & 1200 \\

| Parameters                           | Heat recovery boiler |
|--------------------------------------|----------------------|
| Rated efficiency                     | 89.1%                |
| Upper limit of power (kW)            | 350                  |
| Lower limit of power (kW)            | 20                   |
| Operation and maintenance costs (yuan·kW⁻¹) | 0.13                |
| Active output rise rate (kW·h⁻¹)     | 500                  |
| Active output decrease rate (kW·h⁻¹) | 500                  |

**Table 3.** Heat recovery boiler parameters.

5.2. *Capacity configuration optimization of multi-energy complementary microgrid*

According to the parameters of each component and the optimization model of multi-energy complementary microgrid system capacity configuration and operation scheduling, this example is optimized. The optimized configuration results are shown in table 4.

**Table 4.** Capacity configuration optimization results.

| Number of equipment    | Calculation results |
|------------------------|---------------------|
| Gas turbine            | 1                   |
| Electric energy storage| 5                   |
| Cooling energy storage | 6                   |
| Heating energy storage | 3                   |
| Heat recovery boiler   | 2                   |
| Economic costs (yuan)  | 156 368.05          |
| Contact line power volatility rate | 5.32%            |

5.3. *Operation scheduling optimization of multi-energy complementary microgrid*

According to the parameters of each component and the optimal scheduling strategy of multi-energy complementary microgrid system, this example is optimized. After the calculation, the optimal scheduling operation strategy is obtained, as shown in figure 10.
5.4. Algorithm convergence analysis
In this paper, an improved particle swarm optimization algorithm with extremal variation factor is used. Based on the specific parameters in the example, the particle swarm size is selected: particle number \( N = 300 \); particle dimension \( D = 144 \). In order to verify the correctness of the convergence results, 1000 iteration depths are given. In this paper, the multi-energy complementary microgrid capacity configuration and operation scheduling optimization models, the basic particle swarm optimization algorithm and the improved particle swarm optimization algorithm are used for multiple optimization operations. The final results are shown in table 5.

| Algorithm type                      | Number of iterations | Operating costs (yuan) |
|-------------------------------------|----------------------|------------------------|
| Basic particle swarm optimization   | 318                  | 25 166                 |
| Improved particle swarm optimization| 265                  | 23 649                 |

According to table 5, although the convergence speed of the basic particle swarm algorithm is fast, it is easy to fall into a local optimum, leading to the worst convergence accuracy. The improved particle swarm optimization adopted in this paper takes into account both the convergence speed and the convergence accuracy, and has achieved good results in multi-objective and multi-dimensional complex optimization problems.

6. Conclusion
In this paper, based on the introduction of the system structure of multi-energy complementary microgrid, an optimization model for capacity configuration and operation scheduling of multi-energy complementary microgrid is established. The improved particle swarm optimization algorithm is used to solve the optimization problem of the system and the rationality of the proposed optimization strategy is verified.

- An optimization model for the capacity configuration and operation scheduling of multi-energy complementary microgrid is established, and the economy and the fluctuation of the microgrid connection line are taken as the optimization objectives. The power balance constraints, output power constraints, energy storage components energy constraints and multi-energy complementary microgrid and grid energy exchange constraints are considered in this model. The solution results show that the configuration results obtained by the optimization model established in this paper have lower total economic costs and microgrid contact line power volatility rate.

- A multi-energy complementary microgrid capacity configuration and operation scheduling optimization strategy was proposed. The optimization goal was to minimize the operation and maintenance costs and minimize the volatility rate of the microgrid contact line power. Consider the unit's minimum continuous operation/outage constraints, climbing rate
The above model is solved by the improved particle swarm optimization algorithm considering the extreme value variation. The convergence analysis of the algorithm verifies the feasibility and effectiveness of the improved particle swarm algorithm proposed in this paper.

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References
[1] Cheng L, Zhang J, Huang R L, Wang C P and Tian H 2017 Case analysis of multi-scenario planning based on multi-energy complementation for integrated energy system Electr Power Autom Eq 37 282-7
[2] Wang W L, Wang D, Jia H J, Cheng Z Y, Guo B Q, Zhou H M and Fan M H 2016 Review of steady-state analysis of typical regional integrated energy system under the background of energy internet Proc Chin Soc Eletrical Eng 36 3292-305
[3] Li X, Hui D and Lai X 2013 Battery energy storage station(BESS)-based smoothing control of photovoltaic (PV) and wind power generation fluctuations IEEE Trans Sustain Energy 4 464-73
[4] Jiang S, Qiao Y, Xu Fei, Nie H Z and Hu D 2013 Capacity optimization and sensitivity analysis of cogeneration system of wind power and energy storage Automat Electr Power Sys 37 16-21
[5] Ai Q and Hao R 2018 Optimal allocation model for multi-energy capacity of virtual power plant considering conditional value-at-risk Automat Electr Power Sys 42 2-10
[6] Zhang B H and Long W D 2006 An optimal sizing method for cogeneration plants Energ Buildings 38 189-95
[7] Xu H, Jiao Y, Pu L, He N, Wang Y and Tan Z F 2017 Stochastic scheduling optimization model for virtual power plant of integrated wind-photovoltaic-energy storage system considering uncertainty and demand response Power Syst Technol 41 3590-7
[8] Kong X Q, Wang R Z and Huang X H 2005 Energy optimization model for a CCHP system with available gas turbines Appl Therm Eng 25 377-91
[9] Yokoyama R, Hasegawa Y and Ito K 2002 A MILP decomposition approach to large scale optimization in structural design of energy supply systems Energ Convers Manage 43 771-90
[10] Xu F, Min Y, Chen L, Chen Q, Hu W, Zhang W L, Wang X H and Hou Y H 2014 Combined electricity-heat operation system containing large capacity thermal energy storage Proc Chin Soc Eletrical Eng 34 5063-72
[11] Lu Y and Xu J 2016 Wind power hybrid energy storage capacity configuration based on wavelet packet decomposition Power Syst Prot Control 44 149-54
[12] Chen Z Y, Wang D, Jia H J, Wang W L, Guo B Q, Qu B and Fan M H 2017 Research on optimal day-ahead economic dispatching strategy for microgrid considering P2G and multi-source energy storage system Proc Chin Soc Eletrical Eng 37 3067-77
[13] Zhang Y 2008 Multi-objective optimization of economic dispatch problem based on stochastic weighted sum method and multi-attribute decision making Power Syst Technol 36 64-7
[14] Luo P, Yang T M, Lou S H and Wu Y W 2016 Spectrum analysis based capacity configuration of hybrid energy storage in microgrid Power Syst Technol 40 376-81
[15] Kang M J, Xu H, Wang J Q, Li J K and Chen K 2017 Prediction of battery life in energy storage system based on rain flow count method under pulsed load situation Microcom Applications 36 84-7

[16] Meng M, Wu Y F and Su Y H 2018 The optimization of hybrid energy storage capacity considering the utilization rate of tie lines in microgrid Mod Electr Power 35 39-44