Multi-objective sequential CHP Placement Based on Flexible Demand in Heat and Electricity Integrated Energy System

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Abstract. In order to improve the overall energy efficiency, one of the important trends in the field of energy is the construction of integrated energy systems. In the energy Internet, the comprehensive demand response makes use of the coupling and complementary relationship between different forms of energy, such as electricity and heat, and carries out the coordinated optimization of energy conversion equipment on the demand side to stimulate the flexibility of the comprehensive energy network, which is conducive to improving energy utilization efficiency and reducing energy supply and consumption cost. In this paper, considering the comprehensive demand side response of electricity and heat, an optimal configuration scheme of combined heat and power (CHP) unit is proposed. The scheme takes voltage amplitude, integrated network loss and economic cost as the comprehensive optimization objective. In order to effectively solve the above problems, this paper applies the sequence configuration strategy, adopts the direct power-thermal power flow method, weighted summation method and improved genetic algorithm to solve the above problems. Finally, the simulation of real medium voltage distribution network in Australia was carried out by MATLAB programming, which verified the rationality and superiority of the model.

1. Introduction

In recent years, with the climate change and the enhancement of people's environmental awareness, the traditional energy system has gradually transitioned to the direction of low-carbon system and sustainable energy system [1]. The integrated energy systems (IES), as an effective measure to improve energy efficiency, has developed rapidly in recent years. Thermo-electric integrated energy system based on cogeneration unit is one of the most important forms [2]. CHP units are being studied around the world. In Denmark, the CHP provides 40% of district heating [3]. In northern China, CHP has been installed in more than 300 cities and provides heating for 40% of the population [4].

Although the CHP unit is developing rapidly, it also faces many problems [5]. CHP units are limited by heating network hardware, and are mostly located at the side of distribution, measurement and distribution network. First, in the context of the international power market, the capacity profit of CHP unit is significantly affected by the output fluctuation of distributed new energy [6]. Secondly, there is a positive correlation between the output power of CHP unit and that of thermal energy. At the peak of users' thermal demand, the large output of CHP unit and the output of distributed new energy
will lead to local voltage increase, and unreasonable scheduling will lead to wind and light abandoning, which reduces the advantages of the comprehensive energy system [4].

To this, domestic and foreign experts put forward a lot of Suggestions and methods. Control: considering the cogeneration characteristics of fuel cells can alleviate the unit characteristic limitation of "heat determines power", reduce the "wind abandon" of the system, and improve the overall operating economy of the energy network [7]. Considering the coordination between the online revenue and penalty cost of the optimal operation of the combined system with the uncertainty of wind power output, the optimal operation strategy of the wind farm and cogeneration with the highest revenue can be obtained [8]. Obviously, the above research can increase the benefits of CHP units to a certain extent, but the cost of unreasonable VHP unit configuration is much higher than this benefit. Therefore, in terms of configuration, literature [9-10] studies the coupling of CHP unit with electric or thermal energy storage. However, these measures are more suitable for district heating of relatively small cogeneration devices. However, for large capacity cogeneration units, it is difficult to centrally install the corresponding capacity of thermal storage. Literature [11] considered the demand response of electrical/thermal load and the thermal/electrical coupling between supply and demand, smoothed the thermal/electrical load curve on the energy supply side, and corrected the configuration capacity. However, the processing of the electro-thermal coupling elements and the optimization target are too single, and the influence of distributed power supply is not fully considered.

In order to solve the above problems, a CHP multi-objective optimal configuration model based on network loss, voltage amplitude and economic cost was proposed in this study, taking into account the comprehensive demand side response of electricity and heat. At the end of the paper, the sequence configuration strategy is applied to carry out MATLAB programming simulation for the real medium voltage distribution network in Australia, which proves the rationality and superiority of the multi-objective optimal configuration model of CHP proposed in this paper.

2. Heat and Electricity Integrated Energy System

The system is divided into temperature model and flow model. Among them, the temperature model reflects the temperature change of the hot medium flowing through the pipe in the heating network, and the flow model of the heating network system reflects the flow and intersection of the pipe in the heating network.

2.1. Flow model

When passing through the pipeline, the water temperature decreases with the loss of heat energy, which is related to the environmental temperature, the length of the pipeline and the temperature and flow rate of internal water [12]:

\[ T_{\text{end}} = (T_{\text{start}} - T_a) e^{-\frac{\lambda L}{C_p}} + T_a \]  

(1)

Which \( T_{\text{start}} \) and \( T_{\text{end}} \) start node end node and represent the pipe water temperature (°C); \( T_a \) Is the environment temperature (°C); \( \lambda \) is the coefficient of heat transfer per unit length of pipe (\( W \cdot m^{-1} \cdot ^\circ C^{-1} \)); \( L \) is the length of the pipe (m); \( C_p \) It's the specific heat of water (\( J \cdot kg^{-1} \cdot ^\circ C^{-1} \)).

2.2. Temperature model

The junction node of pipeline, where the water flow through different temperatures converge with each other, is similar to kirchhoff's voltage law [12], which can be expressed as:

\[ (\sum m_{\text{out}}) T_{\text{out}} = \sum (m_{\text{in}} T_a) \]  

(2)

Which \( T_{\text{out}} \) and \( T_{\text{in}} \) respectively intersection of each outlet temperature and inlet temperature (°C); \( m_{\text{out}} \) and \( m_{\text{in}} \) respectively represents the flow rate of each outlet and the flow rate of each inlet at the junction point (kg·s⁻¹).
3. Multi-objective optimization configuration model

3.1. Optimization subobjective

3.1.1. Economic cost. Economic cost is an important factor in CHP unit configuration. Generally, the configuration cost of CHP unit involves the initial purchase and installation cost, as well as the operation and maintenance cost [11], which is defined as follows:

\[ f_1 = C_{PI} + \sum P_{CHP} \times C_{OM} = \frac{C_{OM} \times \sum P_{CHP}}{L_n \times \eta_{MT}} + \sum P_{CHP} \times C_{OM} \]  

Which \( C_{PI} \) is initial purchase and installation costs; \( C_{OM} \) is Cost for operation and maintenance. \( C_{gas} \) is the price of gas. \( L_n \) is the low calorific value of natural gas. \( \eta_{MT} \) is Generating efficiency for micro gas turbines. \( \sum P_{CHP} \) is the total capacity of CHP unit in the whole network.

3.1.2. Voltage amplitude. In this paper, the objective function is established by the deviation between the actual value of each bus voltage and its rated value as follows:

\[ f_2 = \sum_{i=1}^{N} (V_N - V_i) \]  

Which \( V_N \) is the rated voltage of each phase of the bus. \( V_i \) is the actual voltage of the i bus.

3.1.3. Network loss. In order to ensure reasonable network loss, this paper calculates the annual network loss based on three typical load grades.

\[ f_3 = \sum_{k=1}^{3} T_k \times PL_k \]  

which, \( k \) are three typical load grades, namely high, medium and low. The corresponding \( T_k \) is the total annual duration under the load grade. In addition, \( PL_k \) is the average network loss under load grade, as shown in equation (6) below:

\[ PL_k = \sum_{l=1}^{n-1} PL_{lk} \times k = 1,2,3 \]  

Which, \( PL_{lk} \) is the power loss of the fourth branch under the load grade.

3.1.4. Electricity demand side response cost. The implementation standard of the interruptible load project is: during the 7~8 months (calculated as 30 days per month) when the distribution network has the highest load, the load nodes implemented by the project will be interrupted for 2h every day, and the proportion of interrupted load is up to 30%. Purchase cost is the total load of the distribution network deducting the amount of electricity saved by interruptible load. Its definition is as follows:

\[ f_4 = \sum_{k=k}^{K} P_{lk} \times T_{lk} \times p_e + p_h \times \left( P - \sum_{k=k}^{K} P_{lk} \right) \times T_{max} \]  

Where, \( k \) and \( K \) are the nodes and their set of nodes of users participating in the interruptible load project. \( P_{lk} \), \( T_{lk} \) are the interruption load and interruption time of the KTH user, \( p_e \) are the unit compensation cost of the interruptible load, \( P \) are the total active power of the distribution network, and \( T_{max} \) are the maximum utilization hours of the annual load of the distribution network.

In the two months from December to January of the next year (calculated by 30 days per month) when the heat load is the highest, the response is conducted with the ratio of electricity and heat energy generated by the CHP unit to reach the highest utilization rate of the CHP unit. Therefore, during the day, due to the output of the distributed power supply, the house heat source is provided by
the electric heat element, and the CHP unit needs to calculate the additional 2h of thermal output loss every day. Its definition is as follows:

\[ f_5 = \sum_{k \in K} P_{HLk} \times T_{HLk} \times C_H \]  

(8)

Where, \( k \) and \( K \) are the nodes and their set of nodes of the users participating in the electric heat transfer project respectively, \( P_{HLk}, T_{HLk} \) are the electric heat transfer load and electric heat transfer time of the KTH user respectively, and \( C_H \) are the unit compensation and additional loss cost of electric heat transfer load.

3.2. Weighted summation method

In order to reasonably configure the effect, this paper adopts the weighted summation method to transform the multi-objective problem into a single-objective problem [13] for solving.

\[ F = \sum_{i=1}^{s} w_i J_i = \sum_{i=1}^{s} w_i \frac{f_i}{f_i^{\text{max}}} \]  

(9)

where:

\[ \sum_{i=1}^{s} w_i = 1, w_i \geq 0 \]  

(10)

As shown in equations (9) and (10), in the weighted sum process, \( w_i \) is the corresponding weight of the target. In order to ensure that the assigned weight can accurately reflect the weight distribution, each sub-objective function needs to be standardized, and each objective is usually divided by its maximum value [14].

3.3. Objective function

After taking into account equipment and network constraints, the CHP unit optimal configuration model proposed in this study is as follows:

\[ \min F \]  

(11)

\[ \begin{align*}
& P_{Li} - P_{CHPi} + V_i \sum_{j \in i} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) = 0 \\
& Q_{Li} + V_i \sum_{j \in i} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) = 0 \\
& V_{\text{min}} \leq V_i \leq V_{\text{max}} \\
& P_{\text{CHPi}}^{\text{min}} \leq P_{\text{CHPi}} \leq P_{\text{CHPi}}^{\text{max}} 
\end{align*} \]  

(12-14)

Where, equation (12) is the equality constraint, in addition, equations (1) and (2) also belong to the equality constraint. \( P_{Li}, Q_{Li} \) is the active (reactive) power of the bus in the first phase. \( P_{\text{CHPi}} \) is the active input power of CHP. In addition, equations (13) and (14) are inequality constraints, and are voltage upper and lower limit constraints and CHP output constraints, respectively. Where, \( P_{\text{CHPi}}^{\text{min}}, P_{\text{CHPi}}^{\text{max}} \) are the minimum and maximum values of CHP capacity respectively, \( V_{\text{min}} \) and \( V_{\text{max}} \) are the upper limits under voltage, which are set as 6% of the rated value in this paper.

4. Solution algorithm and configuration strategy

CHP multi-objective optimal configuration problem (equation (1-11)) is essentially an optimal power flow (OPF) problem. In this paper, the direct electric - thermal power flow method and improved genetic algorithm are used. In addition, all the simulation in this paper is based on MATLAB programming.

4.1. Direct current method of electricity and heat

In order to ensure that the power flow problem defined in equation (1-11) can be effectively solved, this paper adopts an efficient power flow algorithm: electro-thermal direct power flow method.
Direct power-thermal power flow method is based on direct power flow method [16]. Based on the special topological characteristics of distribution network, power flow of power network and heat network can be directly solved by two constant matrices (node branch incidence matrix and branch impedance matrix). The iterative equations are shown in equations (15) and (16).

\[
\begin{align*}
\Delta V &= BCBV \cdot A \cdot \Delta I \\
V &= V^1 - \Delta V
\end{align*}
\]

(15)

\[
\begin{align*}
m &= A \cdot m_{\text{Load}} \\
C_r \cdot T_{\text{Load}} &= b_r
\end{align*}
\]

(16)

Where, BCBV is the branch impedance matrix, A is the node branch correlation matrix, V^1 is the grid bus rated voltage matrix, and the above matrix is the constant matrix determined by the network state. ΔV represents the voltage drop matrix of the power grid bus, V represents the voltage matrix of the power grid bus, m represents the heat load flow matrix of the heating network branch, m_{Load} represents the heat load flow in the heating network;

4.2. Improved genetic algorithm

The CHP multi-objective optimal allocation model established in equation (11) above is a typical mixed integer nonlinear programming problem in mathematics. At present, there are many algorithms to solve such problems, among which genetic algorithm is one of the most effective. In order to ensure the optimization and efficiency of the solution at the same time, this study adopts the adaptive genetic algorithm proposed in literature [17]. As shown in equation (17-18), the algorithm dynamically adjusts the crossover mutation probability according to the evolutionary state:

\[
p_c = \begin{cases} 
  k_1 \left( \frac{f_{\text{max}} - f'}{f_{\text{max}} - \bar{f}} \right), & f' \geq \bar{f} \\
  k_2, & f' < \bar{f} 
\end{cases}
\]

\[
p_m = \begin{cases} 
  k_3 \left( \frac{f_{\text{max}} - f}{f_{\text{max}} - \bar{f}} \right), & f \geq \bar{f} \\
  k_4, & f < \bar{f} 
\end{cases}
\]

(17)

(18)

Where, PC and PM represent crossover rate and mutation rate respectively, and represent individual fitness values for crossover and mutation operation respectively, f_{\text{max}} represents maximum fitness of the population and average fitness of the population, and k1, k2, k3 and k4 [0,1] are crossover mutation coefficients respectively. The introduction of dynamic crossover mutation probability can not only avoid the decline of convergence caused by too large value, but also avoid falling into local optimization in the middle and late stage of iteration and increase the ability of global optimization.

4.3. Sequence configuration policy

The existing location configuration methods usually only carry out sensitivity analysis once, and then select several buses with high sensitivity for configuration. However, alternative busbars are usually close to each other in position, which may lead to overcompensation when configured [5]. Therefore, this paper proposes a CHP sequential configuration strategy, as shown in figure 1.

Step 1: analyze the loss sensitivity of the bus before CHP configuration.

Step 2: compare the sensitivity of each bus and select the bus with the highest sensitivity as the configuration position of CHP.

Step 3: determine CHP configuration capacity using the established CHP multi-objective optimization configuration model (1-16).
Step 4: calculate the value of the total objective function (equation (11)) after configuration and compare it with that before configuration. If, it indicates that the network is significantly optimized after this configuration and the configuration cost is controlled within a reasonable range, proving that this configuration is reasonable and feasible, then repeat steps 1-3 to execute the next CHP configuration; Otherwise, the configuration is no longer reasonable, give up the configuration, the end of the process.

![Flow chart of CHP sequence configuration policy.](image)

**Figure 1.** The flow chart of CHP sequence configuration policy.

5. **Simulation analysis**

5.1. **Simulation network and parameter setting**

In order to verify the proposed CHP multi-objective optimal configuration model, this paper conducts simulation based on the real unbalanced distribution network of Australia's 20 nodes with medium voltage 132/22kv, as shown in figure 2. The configuration distribution of high, medium and low load grades is shown in table 1. Sub-objective function parameters, weight setting and GA parameters are shown in table 2.
Table 1. Load profiles of peak, medium and light conditions

| Load (MW) | Electric load | Thermal load |
|-----------|---------------|--------------|
| Peak      | 17.85         | 5.46         |
| Medium    | 13.46         | 4.11         |
| Light     | 9.44          | 2.88         |

Table 2. Load profiles of peak, medium and light conditions

| Objective function | Weight coefficient | GA parameter | Economic parameter |
|--------------------|--------------------|--------------|--------------------|
| T1 (h)             | 1000               | w2           | 0.2                | k1  | 1 | c_{om} | 20 ¥ |
| T2 (h)             | 6760               | w3           | 0.2                | k2  | 0.5 | c_{sm} | 1.88 ¥/m³ |
| T3 (h)             | 1000               | w4           | 0.15               | k3  | 1 | L_n  | 9.7 kW/m³ |
| w1                 | 0.3                | w5           | 0.15               | k4  | 0.5 | \eta_{int} | 0.35 |

5.2. The simulation results

5.2.1. Overall performance. The positions and capacities of the CHP after optimized configuration of each order are shown in Table 3. Specifically, according to the multi-objective optimal configuration model proposed in the second section, the most reasonable configuration locations are at node 12 and node 8, and their installed capacities are respectively 12 MW and 3 MW.

Table 3. Selected site and installed size of each placement

| Location | Base case | 1st | 2nd |
|----------|-----------|-----|-----|
| Location | —         | 12  | 8   |
| Capacity/MW | — | 12  | 3   |

5.2.2. Each subobjective function. After CHP sequence configuration, the total objective function decreases (Figure 3), and the values of each sub-objective function also decrease accordingly. After the third configuration, although the state objectives of each network are reduced, the economic cost is greatly increased, making the total objective function rise. Therefore, the third configuration is not carried out.
5.2.3. Demand side response comparison. In this paper, four cases are set as follows: case 1: configuration of CHP unit without demand side response; Case 2: the CHP unit configuration considering the traditional power demand side response; Case 3: configuration of CHP unit considering thermal demand side response; Case 4: the CHP unit configuration of the power-thermal integrated demand side response proposed in this paper.

The number of configurations and the total configuration capacity are shown in table 4. By comparing table 4, it can be seen that the number of configurations in case 1 is the most, which is three. And the configuration times of case 2, 3, 4 is same, it is twice. However, the overall configuration capacity is the smallest in case 4. Obviously, the configuration of CHP units that take into account the combined demand side response of electricity and heat can save installation costs and bring greater economic benefits.

| Case   | weight coefficient | GA parameter |
|--------|--------------------|--------------|
| Case 1 | 3                  | 16.2         |
| Case 2 | 2                  | 15.3         |
| Case 3 | 2                  | 15.8         |
| Case 4 | 2                  | 15           |

6. Conclusion
Considering the demand side response of thermoelectricity, a multi-objective optimal configuration model of CHP is established in this paper, taking into account the network loss, voltage amplitude and economic cost. In order to accurately reflect the optimization objectives, this paper adopts the weighted summation method to transform the multi-objective problem into a single-objective problem for solving. At the same time, in order to solve the optimal power flow problem of CHP optimal configuration quickly and efficiently, this paper adopts the electric-thermal direct power flow method and the improved genetic algorithm. Moreover, in order to configure reasonably and effectively, this paper applies the sequential configuration strategy. Finally, the simulation of real medium voltage distribution network in Australia is carried out, and the results show that the order multi-objective optimal configuration of CHP proposed in this paper is feasible and effective. This paper puts forward a new scheme for comprehensive energy optimization planning.
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