Study on the two-layer optimal configuration strategy of wind abandoning and absorption in CHP micro-grid

HongxiaYu¹a and FuweiYang¹
¹School of Information Science and Engineering, Shenyang University of Technology, Shenyang, Liaoning, 110870, China
²hongxiayu08@sut.edu.cn
³Corresponding author’s e-mail: yangfuwei67@163.com

Abstract. In order to solve the problem of wind abandoning for micro-grid in the heating season. Adding electric boiler and thermal storage device to micro-grid and using configuration strategy is an effective way, the effective configuration scheme is also very important to it. A two-layer model optimization method that introduces scheduling in configuration is proposed, the models and constraints of the main units in the micro-grid are given, the upper layer aims to minimize the sum of the total operation cost and configuration and maintenance cost of the micro-grid during the heating period, the lower layer aims to minimize the integrated operation cost of the 24-hour micro-grid. Simulation results show that, the proposed method can effectively reduce the operation cost and wind abandoning power of micro-grid, the optimal configuration scheme is obtained.

1. Introduction

In order to cope with the problem of depletion of fossil energy, it is necessary to increase the use rate of clean energy. China's wind energy resources are considerable and the potential for wind power generation is huge[1-2], but the problem of wind power acceptance is an important problem in the development of wind power. Reference[3-5] increased the configuration of electric boilers in thermal power plants, which improved the economics of the micro-grid and reduced the coal consumption of the unit. With the rapid development of energy storage technology in recent years, the problem of wind abandonment has been solved by configuring thermal storage devices[6]. Reference[7-8] uses energy storage in the power system, increasing the flexibility of the unit, and thus improving the ability of the thermal generation unit to participate in the peak regulation of the micro-grid. And when the electric boiler and the thermal storage device are configured together, there will be better results[9].

This article aims at the combined heat and power micro-grid with electric boiler and thermal storage device, a two-layer model optimization method that introduces scheduling in configuration is proposed. The configuration cost of the upper layer is calculated through the life cycle cost[10]. And the integrated operation cost of the lower layer considers the cost of wind curtailment[11]. The model needs to satisfy electric load constraints and heat load constraints. And the configuration scheme is also very important, it affects the total cost. The example shows that this method can effectively reduce the operation cost of micro-grid and reduce the abandoned wind power, and the optimal configuration scheme is obtained.
2. Micro-grid and output unit model

2.1. Micro-grid chart
The structure diagram of the micro-grid is shown in ‘figure 1’. Compared with the traditional combined heat and power micro-grid, an electric boiler is arranged on the heat load side, and a thermal storage device is arranged on the CHP unit side. The electric boiler consumes micro-grid electricity for heating. The thermal storage device can store the heat when the CHP unit generates more heat, or it can release heat when the heat generation is insufficient, allowing them to cooperate to achieve the purpose of eliminating wind and reducing costs.

![Figure 1. CHP micro-grid with electric boiler and thermal storage device](image)

2.2. Thermal generation unit model
Thermal generation units generate electricity by consuming fuel, and their electrical output constraints and climbing constraints are as follows.

\[
P_{i,\text{min}} \leq P_i^t \leq P_{i,\text{max}} \quad (1)
\]

\[
P_d \leq P_i^t - P_{i-1}^t \leq P_u \quad (2)
\]

Where, \( P_{i,\text{min}} \) and \( P_{i,\text{max}} \) are respectively the minimum value and maximum value of the electric quantity that the \( i \)th thermal generation unit can produce at time \( t \), \( P_i^t \) is the electric power of the \( i \)th thermal generation unit at time \( t \), \( P_d \) and \( P_u \) are respectively the lower limit and upper limit of the climbing rate of the thermal generation unit.

2.3. CHP unit model
The range of its electric output is determined by its heat output. With the increase of users' heat load requirements, the electric power range of CHP unit decreases accordingly. The thermoelectric characteristics and climbing constraints of the units are as follows.

\[
\begin{align*}
P_{e,\text{min}} - C_v P_{h} & \leq P_e \leq P_{e,\text{max}} - C_v P_{h} & & P_{h} \leq P_{he,\text{max}} \\
P_{e,\text{min}} - (C_v + C_h)P_{he,\text{max}} + C_h P_{h} & \leq P_e \leq P_{e,\text{max}} - C_v P_{h} & & P_{h} \geq P_{he,\text{max}}
\end{align*}
\]

(3)
\[ P_{e,d} \leq P'_{e,j} - P'_{e,j-1} \leq P_{e,u} \]  \hspace{1cm} (4)

Where, \( C_v \) and \( C_s \) are the coefficients respectively, \( P_{e,\text{min}} \) and \( P_{e,\text{max}} \) are the minimum and maximum electric output values of the CHP unit, \( P_h \) is the heat power, \( P_{e,d} \) and \( P_{e,u} \) are the lower limit and upper limit of the climbing rate of the unit's electric power, and \( P'_{e,j} \) is the electric power values of the jth unit at time t.

2.4. Electric boiler output model
The electric boiler can convert electric energy into heat energy, reducing pollution. Its electric heat conversion model is as follows.

\[ P_{GH} = \eta P_{GE} \]  \hspace{1cm} (5)

\[ 0 \leq P_{GE} \leq P_{GE,\text{max}} \]  \hspace{1cm} (6)

Where, \( P_{GH} \) and \( P_{GE} \) are respectively the heat power output and the electric power consumed by the electric boiler, and \( \eta \) is the electric heat conversion efficiency. The electric power of the electric boiler shall be within the upper limit \( P_{GE,\text{max}} \) range of the electric power.

2.5. Model of thermal storage device
The thermal storage device can be used in the storage of peak-load heat energy of micro-grid power. Its model is as follows.

\[ Q_t = Q_{(t-1)} + \Delta Q_t \]  \hspace{1cm} (7)

\[ \begin{cases} \Delta Q_t = P \cdot \lambda_{cha} & 0 \leq P \leq pess \\ \Delta Q_t = P / \lambda_{dis} & -pess \leq P \leq 0 \end{cases} \]  \hspace{1cm} (8)

\[ Q_{\text{min}} \leq Q_t \leq Q_{\text{max}} \]  \hspace{1cm} (9)

Where, \( Q_t \) represents the thermal storage of the thermal storage device at time t, \( P \) is its power, positive is heat storage and negative is heat release, \( \lambda_{cha}, \lambda_{dis}, pess \), \( Q_{\text{min}} \) and \( Q_{\text{max}} \) are respectively heat storage efficiency, heat release efficiency, maximum heat storage and release power, minimum and maximum heat storage.

3. Optimization model and constraints

3.1. The establishment of upper optimization model
After adding electric boilers and thermal storage devices to the traditional combined heat and power supply micro-grid, the rigid constraint of "heat determines power" of the CHP unit is broken, the space of wind abandoning and absorption is improved, and the operation of the entire micro-grid is more flexible. However, the choice of how much power of electric boiler and how much capacity of thermal storage device will affect the total operating cost of the micro-grid. Therefore, this paper establishes a two-layer model to introduce scheduling in the configuration for optimal configuration. The upper layer aims to minimize the sum of the total operation cost and configuration and maintenance cost of the micro-grid during the heating period.

\[ \min F_{\text{sum}} = \min \sum_{d=1}^{D} F + C_{gm} + C_{wh} \]  \hspace{1cm} (10)

In the formula, \( F_{\text{sum}} \) is the total operation cost of the micro-grid during the heating period, \( D \) is the heating days, \( F \) is the operation cost of the 24 hours per day micro-grid, \( C_{gm} \), \( C_{wh} \) are
respectively the purchase and configuration cost of the electric boiler and the thermal storage device, the maintenance cost, and the formula is as follows.

\[ C_{gm} = \frac{C_{buy} - C_{retire}}{N} \] (11)

\[ C_{buy} = aX_1 + bX_2 \] (12)

\[ C_{retire} = 0.2 \cdot C_{buy} \] (13)

\[ C_{wf} = K_{GE}X_1 + K_{CR}X_2 \] (14)

Where, \( C_{gm} \) calculated according to the whole life cycle, \( X_1 \) and \( X_2 \) are respectively the power of electric boiler and the capacity of the thermal storage device, \( a \) and \( b \) are corresponding to the unit price, \( K_{GE} \) and \( K_{CR} \) are the corresponding maintenance cost parameters.

3.2. The establishment of lower optimization model

The upper layer will transmit the configuration scheme to the lower layer, and the lower layer will aim to minimize the integrated operation cost of the 24-hour micro-grid under this scheme.

\[ \min F = \min \sum_{t=1}^{T} (F_h(P'_h) + F_e(P'_e, P'_{h,j}) + C_{qf} + C_{jh}) \] (15)

In the formula, \( F_h(P'_h) \), \( F_e(P'_e, P'_{h,j}) \), \( C_{qf} \), \( C_{jh} \) are respectively the operation cost of the thermal generation unit, the operation cost of the CHP unit, the wind abandoning cost and the interactive cost of the electricity with the big grid, and the formula is as follows.

\[ F_h(P'_h) = \sum_{t=1}^{T} \sum_{j=1}^{N} (a \cdot (P'_h)^2 + b \cdot P'_h + c) \] (16)

\[ F_e(P'_e, P'_{h,j}) = \sum_{t=1}^{T} \sum_{j=1}^{R} (a_j \cdot (P'_e, P'_{h,j})^2 + b_j \cdot (P'_e, P'_{h,j}) + c_j) \] (17)

\[ C_{qf} = \lambda P_{qf} \] (18)

\[ C_{jh} = \sum_{t=1}^{T} \sum_{j=1}^{N} P'_{h,j} \cdot C_{dj} \] (19)

Where, unit operation cost can be represented as quadratic form, \( \lambda \) is the cost coefficient of wind curtailment, \( P'_{qf} \) is the wind power, \( P'_{jh} \) is the interactive power with big grid, \( C_{dj} \) is time-of-use electricity price.

3.3. The constraint

In order to ensure the stable and safe operation of the micro-grid, the model should not only satisfy its own constraints, but also meet the heat load balance constraints and electric load balance constraints of the micro-grid, as shown below.

\[ \sum_{j=1}^{R} P'_{h,j} + P'_{GH} - P_{h,load} - P'_{cha} / P'_{dis} = 0 \] (20)

\[ \sum_{i=1}^{N} P'_i + \sum_{j=1}^{R} P'_{e,j} + P'_{wf} - P'_{qf} - P'_{e,load} + P'_{jh} - P_{GE} = 0 \] (21)

Where, \( P_{h,load} \) and \( P_{e,load} \) are the heat load demand and electrical load demand at time \( t \); \( P'_{cha} / P'_{dis} \) are the heat storage power or heat release power of the thermal storage device; \( P'_{wf} \) is the wind power.
4. The example analysis

4.1. The example data
This paper selects the actual data of the power grid of a province in China, and collects the heat load, electric load and wind power output data 24 hours on a typical day of the heating season, is shown in ‘figure 2’, the electric boiler power allocation between 50 MW and 200 MW, is a gear with 50 MW, the thermal storage device capacity allocation between 200 MWH and 500 MWH, with 100 MWH is a gear, a total of 16 kinds of configuration scheme, using genetic algorithm to solve, to find the optimal configuration.

![Figure 2. Heat load, electric load and wind power output](image)

4.2. Configure the results
The comparison table of wind abandon power and operation cost of 16 configuration schemes and traditional combined heat and power micro-grid is shown in ‘table 1’.

| Scheme | Electric boiler power (MW) | Thermal storage capacity (MWH) | Operating cost (Ten thousand yuan) | Configuration cost (Ten thousand yuan) | Maintenance cost (Ten thousand yuan) | Abandon the wind power (MWH) | The total cost (Ten thousand yuan) |
|--------|----------------------------|--------------------------------|----------------------------------|----------------------------------------|--------------------------------------|------------------------------|---------------------------------|
| 1      | 50                         | 200                            | 13388                            | 1040                                   | 5                                    | 963900                       | 14433                           |
| 2      | 50                         | 300                            | 13117                            | 1060                                   | 7                                    | 948940                       | 14184                           |
| 3      | 50                         | 400                            | 13006                            | 1080                                   | 9                                    | 942050                       | 14095                           |
| 4      | 50                         | 500                            | 12999                            | 1100                                   | 11                                   | 941230                       | 14110                           |
| 5      | 100                        | 200                            | 11570                            | 2040                                   | 6                                    | 807770                       | 13616                           |
| 6      | 100                        | 300                            | 11558                            | 2060                                   | 8                                    | 806460                       | 13624                           |
| 7      | 100                        | 400                            | 11553                            | 2080                                   | 10                                   | 805760                       | 13643                           |
| 8      | 100                        | 500                            | 11544                            | 2100                                   | 12                                   | 804740                       | 13656                           |
| 9      | 150                        | 200                            | 10386                            | 3040                                   | 7                                    | 695880                       | 13433                           |
| 10     | 150                        | 300                            | 10367                            | 3060                                   | 9                                    | 693900                       | 13436                           |
| 11     | 150                        | 400                            | 10359                            | 3080                                   | 11                                   | 692920                       | 13450                           |
| 12     | 150                        | 500                            | 10350                            | 3100                                   | 13                                   | 691770                       | 13463                           |
| 13     | 200                        | 200                            | 9492                             | 4040                                   | 8                                    | 609440                       | 13540                           |
| 14     | 200                        | 300                            | 9475                             | 4060                                   | 10                                   | 608210                       | 13545                           |
| 15     | 200                        | 400                            | 9460                             | 4080                                   | 12                                   | 607250                       | 13552                           |
| 16     | 200                        | 500                            | 9432                             | 4100                                   | 14                                   | 606170                       | 13546                           |
| 17     | 0                          | 0                              | 16986                            | 0                                     | 0                                    | 1217385                      | 16986                           |
As can be seen from the table, with the increase of configuration power and capacity, the operation cost of the micro-grid is decreasing, but the corresponding configuration cost and maintenance cost are increasing. Therefore, there is an optimal configuration scheme 9, which can minimize the sum of operation cost and configuration and maintenance cost of the micro-grid.

5. Conclusion
In this paper, it is proposed to add electric boiler and thermal storage device to absorb wind abandoning in the traditional micro-grid of combined heat and power supply:

1) Compared with the traditional combined heat and power supply micro-grid, the electric boiler and the thermal storage device can absorb more wind abandoning, improve the flexibility of the micro-grid and reduce the operation cost after being configured, and the optimal configuration scheme is obtained to configure 150MW electric boiler and 200MWH thermal storage device.

2) In this paper, the typical daily load in the heating season is taken as the load requirement of the whole heating season. The sample is relatively single in analysis and calculation. If more load data are collected for calculation and analysis, the accuracy of the model can be further improved.

Acknowledgments
The authors are grateful for the financial support of the National Natural Science Foundation of China (No. 61803273), the "Seedling raising" project for young scientific and technological talents in Liaoning Provincial Department of Education of China (No. LQGD2019012) and the Natural Science Foundation Guidance Project and key research and development program in Liaoning of China (No. 20180550970).

References
[1] Dai J, Yang X, Wen L. (2018) Development of wind power industry in China: A comprehensive assessment. J. Renewable and Sustainable Energy Reviews, 97: 156-164.
[2] National energy administration. (2018) Wind power grid integration in 2017. http://www.nea.gov.cn/2018-02/01/c_136942234.htm.
[3] Lv Q, Jiang H, Chen T. (2014) Wind power accommodation by combined heat and power plant with electric boiler and its national economic evaluation. J. Automation of Electric Power System, 38(01): 6-12.
[4] Blarke M B. (2012) Towards an intermittency-friendly energy system: Comparing electric boilers and heat pumps in distributed cogeneration. J. Applied Energy, 91(1): 349-365.
[5] Ostergaard P A. (2013) Wind power integration in Aalborg Municipality using compression heat pumps and geothermal absorption heat pumps. J. Energy, 49: 502-508.
[6] Liu W, Wen J, Xie C. (2015) Multi-objective optimization method considering wind power accommodation based on source-load coordination. J. Proceedings of the CSEE, 35(05): 1079-1088.
[7] Deng T, Tian L, Liu J. (2015) A control method of heat supply units for improving frequency control and peak load regulation ability with thermal storage in heat supply net. J. Proceedings of the CSEE, 35(14): 3626-3633.
[8] Yu J, Sun H, Shen X. (2017) Optimal operating strategy of integrated power system with wind farm, CHP unit and heat storage device. J. Electric Power Automation Equipment, 37(06): 139-145.
[9] Cui Y, Chen Z, Yan G, et al. (2016) Coordinated wind power accommodating dispatch model based on electric boiler and CHP with thermal energy storage. J. Proceedings of the CSEE, 36(15): 4072-4081.
[10] Xiu X. (2018) Research on capacity optimization configuration and life cycle economic evaluation method for energy storage system. D. China Agricultural University.
[11] Dai Y, Chen L, Min Y, et al. (2017) Optimal dispatch for joint operation of wind farm and combined heat and power plant with thermal energy storage. J. Proceedings of the CSEE, 37(12): 3470-3479+3675.