Power-Grid Dispatching Method Considering Heat-Power Coupling Characteristics of CHP Units

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Abstract. The dispatching optimization of power grid is to obtain the greatest benefits on the basis of safe and stable operation of the power grid, which is of great significance for the energy-saving, reliability of the power grid. Therefore, a multi-objective model of power grid dispatching which considers the heat-power coupling characteristics of CHP units is developed in this study. The economic benefit and minimum wind power abandonment are taken as optimizing targets in the model. Meanwhile, the detail operation characteristics of condensing power plants and CHP units are considered in this model based on off-design models of power plant. Besides, the regional heat load and power load are scheduled together. Finally, the AHP-entropy method is used to obtain the weights of the two optimizing targets of economic benefit and wind power abandonment, and the multi-objective is converted into a single-objective.

1. Instruction

Power grid dispatching is an effective management method to ensure the safe and stable operation of the power grid [1]. Economic dispatching is the most typical optimization problem of the power grid. The essence of economic dispatching of power grid is to obtain the optimal operation method that meets the constraints of load. It mainly includes two contents, namely the establishment of the dispatching model and the solution of the model.

At present, many scholars have carried out a lot of studies on the establishment of the economic dispatching models. Tian [2] proposed a calculation method for deep peak shaving benefits of coal-fired power plants based on equivalent substitution, and established an economic dispatching model of power grid based on graded depth peaking of coal-fired power plants. Guo et al. [3] presented a distributed economic dispatch strategy based on projected gradient and finite-time average consensus algorithms for smart grid systems, and both conventional thermal power plants and wind turbines were taken into account in the economic dispatch model. Yu et al. [4] studied the strategy of economic power dispatch by using the distributed consensus theory in multi-agent systems. Xing et al. [5] investigated the dynamic economic dispatch problem with energy storage in a smart grid scenario,
aiming at minimizing the aggregate generation costs over multiple periods on condition under constraints. Many methods and algorithms including Coordinated optimization algorithm [6], Lagrange relaxation method [7], Genetic algorithm [8, 9] and Particle swarm optimization algorithm [10, 11], have been applied to solve the dispatching models.

In summary, many in-deep studies have been carried out on economic dispatching of power grid. However, the detail characteristics of combined heat and power (CHP) units are not directly considered in the dispatch models of the power grid. Therefore, a power grid economic dispatching model which considers the coupling characteristics of CHP units is developed in this study. Heat and power loads are dispatched together in this model.

2. Heat-power coupling characteristics of CHP units
Compared with condensing power units, the adjustable range of power for CHP units is limited by several indicators. This phenomena is the so-called heat-power coupling characteristics. To maintain the safe operation of the low-pressure turbine blades, the steam flow rate of the low-pressure turbine cannot be smaller than the minimum condensate flow rate of CHP units. Besides, the live steam of turbine should be lower than the maximum steam flow rate and also be larger than the minimum evaporation flow rate of boiler. When the steam flow rate of the steam turbine is constant, the adjustable range of power load decreases with the increase of the heat load. Therefore, the power load is restricted by the heat load. Taking a single-stage extraction steam turbine as an example, its heat-power characteristics are shown in Fig. 1.

![Fig. 1 Heat-power characteristic of single-stage extraction turbine](image)

In Fig. 1, the area ABCD is the feasible operation domain of a single-stage extraction turbine. The live steam flow rate is the maximum steam flow rate of turbine and minimum evaporation flow rate of boiler in line AB and CD, respectively. The steam flow rate of low-pressure turbine is the minimum condensate flow rate in line BC. It can be seen from Fig. 1 that the power output and the heat output of CHP units have a certain coupling mechanism. When the heat load of the unit is $Q_{hM1}$, its power load varies between $M_1$ and $M_2$, that is, the adjustable range of power load is from $P_{eM2}$ to $P_{eM1}$. Meanwhile, the adjustable range of power load decreases with the increase of the heat load.
3. Multi-objective economic dispatching models consider the coupling characteristics of CHP units

3.1. Objective function

The minimum power generation cost, the minimum operating cost, or the minimum network loss are generally taken as the objective functions in traditional power-grid economic dispatching problem. In this study, the minimum power generation cost is used as the optimization goal, and the cost for start-stop plants is neglected. Besides, the model considers the emission reduction effects of carbon oxides, nitrogen oxides, sulphur oxides and other polluting gases to reflect the environmental benefits of wind power. Taking the air pollutant emissions cost of the plants into the model, and the objective function is as follows:

\[ f_1 = \sum_{i=1}^{N_1} \sum_{t=1}^{T} [C_{ni}(t) + K_e M_i(P_{ni}(t))] + \sum_{i=1}^{N_2} \sum_{t=1}^{T} C_{gi}(t) + K_e N_i(P_{gi}(t), Q_{hi}(t)) \] (1)

Where \( N_1 \) and \( N_2 \) are the numbers of condensing power units and CHP units respectively. \( T \) is the dispatching time. \( C_{ni}(t) \) and \( C_{gi}(t) \) are the fuel costs of condensing power plants and CHP units, respectively. \( M_i \) and \( N_i \) are the pollutant emissions of condensing power plants and CHP units, respectively. \( K_e \) is pollutant emission price. \( P_{ni}(t) \) and \( P_{gi}(t) \) are the powers of condensing power plant \( i \) and CHP unit \( i \) at time \( t \). \( Q_{hi}(t) \) is the heat of CHP unit \( i \) at time \( t \).

The impact of wind power integrated into the power grid needs to be considered in the original economic dispatching. According to the national energy department’s policy for promoting the integration of wind power, wind power is given the priority to access the power grid. Therefore, to minimize the abandonment of wind power, the objective function is as follows:

\[ f_2 = \sum_{i=1}^{N_3} \sum_{t=1}^{T} [P_{wi}(t) - P_{wi}(t)] \] (2)

Where \( N_3 \) is the number of the wind power plants. \( P_{wi}(t) \) and \( P_{wi}(t) \) is the maximum adjustable predicted power and actual power of wind power plant \( i \) at time \( t \), respectively.

The whole objective function is:

\[ \min f = w_1 f_1 + w_2 f_2 \] (3)

Where \( w_1 \) and \( w_2 \) are the weights of the two evaluation indicators of economy and abandonment of wind power, respectively.

3.2. Constraints

(1) Power balance constraint

The sum of power supplied by the coal-fired power plants and wind power plants is equal to the total power load in the area at the same time.

\[ \sum_{i=1}^{N_1} P_{ni}(t) + \sum_{i=1}^{N_2} P_{gi}(t) + \sum_{i=1}^{N_3} P_{wi}(t) = P_L(t) \] (4)

In the formula, \( P_L(t) \) is the power load of the area at time \( t \).

(2) Heat balance constraint

The sum of heat supplied by the CHP units and others heat sources is the same as the total heat load of the area at time \( t \).
\[
\sum_{i=1}^{N_i} Q_{ih} (t) + Q_e (t) = Q_L (t)
\]

(5)

In the formula, \(Q_L (t)\) is the heat load of the area at time \(t\). \(Q_e (t)\) is the heat supplied by others heat sources at time \(t\).

(3) Operation constraints of power plants

There are maximum and minimum power for the coal-fired power plants, and it can be expressed as:

\[
P_{n_{i\text{min}}} \leq P_{ni} (t) \leq P_{n_{i\text{max}}}
\]

(6)

\[
P_{gi_{\text{max}}} \leq P_{gi} (t) \leq P_{gi_{\text{min}}}
\]

(7)

According to the previous section, there is a certain coupling relationship between the power and the heat of CHP units, it can be expressed as:

\[
0 \leq Q_{hi} (t) \leq f_{(AB)i}(Q_{hi}(t)) \quad P_{gi\text{max}} = f_{(CD)i}(Q_{hi}\text{max})
\]

(8)

\[
Q_{hi\text{min}} \leq Q_{hi}(t) \leq f_{(AB)i}(Q_{hi}(t)) \quad P_{gi\text{min}} = f_{(BC)i}(Q_{hi}\text{min})
\]

(9)

The power constraint of wind power plant can be expressed by:

\[
0 \leq P_{wi} (t) \leq P_{w_{i\text{max}}}
\]

(10)

The subscript \(i\) indicates the unit \(i\); \(P_{n_{i\text{min}}}\) represents the minimum power load of the condensing power plant, which is determined by the minimum evaporation flow rate of the boiler. \(P_{n_{i\text{max}}}\) is the maximum power load of condensing power plant, which is determined by the maximum steam flow rate of the turbine. \(P_{gi\text{min}}\) and \(P_{gi\text{max}}\) represent the maximum and minimum power loads of the CHP \(i\) respectively, which are related with the heat load. \(P_{gi\text{min}}, P_{gi\text{max}}, P_{gi\text{C}}\) and \(P_{gi\text{D}}\) are the power corresponding to points A, B, C and D in the heat-power characteristics diagram of CHP unit \(i\), respectively. \(Q_{gi\text{A}}, Q_{gi\text{B}}, Q_{gi\text{C}}\) and \(Q_{gi\text{D}}\) are the heat corresponding to points A, B, C, and D in the heat-power characteristics diagram of CHP unit \(i\), respectively. \(f_{(AB)i}, f_{(BC)i}, f_{(CD)i}\) are the relationship formula of line AB, BC and CD in the heat-power characteristics diagram of CHP unit \(i\), respectively. \(P_{w_{i\text{max}}}\) is the maximum output of wind power plant \(i\).

(4) Climbing rate of power plants

The constraints of climbing rate of power plant can be expressed as follows:

\[
-P_{n_{i\text{down}}} \leq P_{ni} (t) - P_{ni} (t-1) \leq P_{n_{i\text{up}}}
\]

(11)

\[
-P_{gi\text{down}} \leq P_{gi} (t) - P_{gi} (t-1) \leq P_{gi\text{up}}
\]

(12)

\(P_{n_{i\text{down}}}\) and \(P_{n_{i\text{up}}}\) are the maximum downward and upward climbing rates of the condensing power plant \(i\). \(P_{gi\text{down}}\) and \(P_{gi\text{up}}\) are the maximum downward and upward climbing rates of the CHP unit \(i\).
3.3. Solution process
The key to solving the multi-objective problem is to convert the multi-objective problem into a single-objective problem. The weighting method is used in this study. The weight of each indicator is calculated by the analytic hierarchy process (AHP) and entropy weight method based on multiplicative synthesis.

AHP is to decompose the problem into different hierarchical structures. Then, the priority weigh of each element at each level to the previous level is obtained by solving eigenvectors of the judgment matrix. Finally, the method of weighted sum is used to hierarchically merge the final weights of the alternative targets.

The basic of the entropy weight method is to determine the objective weight through the factor variability. If the information entropy of an indicator is smaller, it indicates that the factor is more variability, and the more information is provided. Besides, the role that can be played in the comprehensive evaluation is greater, and the weight is also greater. The method is applied to the above multi-objective model, and the calculation process is as follows.

3.4. Application of the proposed power-grid dispatching method
The optimized power-grid dispatching method is applied in the power-grid dispatching of power-grid of Tianjin City, China. In the application process, the feasible operation domains of CHP units were calculated. Then, the characteristics of CHP units were considered in the power-grid dispatching problem as constraints. The power generation of coal-fired power plants is decreased significantly, which decreased by 63,000 MWh in 2018. More renewable power can be consumed as a results, which increased by 39% in 2018.
4. Conclude
The heat-power coupling characteristics of CHP units has a great influence on the power-grid dispatching. When the heat is constant, the power of a CHP unit can only be adjusted within a certain range. Besides, the adjustment range of the power decreases with increase of the heat load. Therefore, a power grid dispatching model that considers the heat-power coupling characteristics of the CHP units is proposed in this study.

(1) The coal-fired power plants are divided into condensing power plants and CHP units in the proposed model, and the operating characteristics of the two types of coal-fires power plants are considered.

(2) AHP-entropy weight method is used to obtain the two indicators weights of economy and abandonment of wind power. The multi-objective problem can be transformed into single-objective problem by weight method, which lays a foundation for subsequent solution.

(3) The power-grid dispatching method proposed in this study was applied. With this method, more renewable power can be penetrated in the power grid for the detail operation domain of CHP units were considered.

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References
[1] Ding N, Duan J, Xue S, Zeng M, Shen J. Overall review of peaking power in China: Status quo, barriers and solutions. Renew Sust Energ Rev 2015; 42: 503-516.
[2] Xinyu T. Study on Economic Dispatch and Benefits of Regional Power System Considering Deep Adjustment of Thermal Power. Beijing: North China Electric Power University; 2018.
[3] F. G, C. W, J. M, Y. S. Distributed Economic Dispatch for Smart Grids With Random Wind Power. Ieee T Smart Grid 2016; 7: 1572-1583.
[4] Yu W, Li C, Yu X, Wen G, Liu J. Economic power dispatch in smart grids: a framework for distributed optimization and consensus dynamics. Science China Information Sciences 2017; 61: 12204.
[5] Xing H, Lin Z, Fu M, Hobbs BF. Distributed algorithm for dynamic economic power dispatch with energy storage in smart grids. Iet Control Theory a 2017; 11: 1813-1821.
[6] Hamdi M, Chaoi M, Idoumghar L, Kachouri A. Coordinated consensus for smart grid economic environmental power dispatch with dynamic communication network. Iet Gener Transm Dis 2018; 12: 2603-2613.
[7] Cheng S, Feng Y, Wang X. Application of Lagrange Relaxation to Decentralized Optimization of Dispatching a Charging Station for Electric Vehicles. Electronics-Switz 2019; 8.
[8] Nagapurkar P, Smith JD. Techno-economic optimization and social costs assessment of microgrid-conventional grid integration using genetic algorithm and Artificial Neural Networks: A case study for two US cities. J Clean Prod 2019; 229: 552-569.
[9] Jafari E. Determining Optimal Strategy of a Micro-Grid through Hybrid Method of Nash Equilibrium-Genetic Algorithm. INTERNATIONAL JOURNAL OF EMERGING ELECTRIC POWER SYSTEMS 2019; 20.
[10] Yadav NK. Hybridization of Particle Swarm Optimization with Differential Evolution for Solving Combined Economic Emission Dispatch Model for Smart Grid. J Eng Res-Kuwait 2019; 7: 244-257.
[11] Yang Y, Wei B, Qin Z. Sequence-based differential evolution for solving economic dispatch considering virtual power plant. Iet Gener Transm Dis 2019; 13: 3202-3215.