

Optimal Energy Flow Calculation of Combined Natural Gas, Cooling, Heating and Power Joint Supply Park Microgrid

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ABSTRACT

The combined natural gas, cooling, heating and power joint supply (CNCHP) microgrid of an industrial park has the advantages of cascaded use of energy, which can effectively improve energy efficiency and reduce pollutant emissions. In this paper, the optimal energy flow calculation model of CNCHP microgrid is established. Minimizing the total running cost of the microgrid is as the objective function, and the network operation characteristics of the cooling network, heating network, power supply network and gas supply network is considered. The model includes the loss characteristics and security operation constraints of various types of energy networks, and the obtained optimal operation schedule can meet the actual operational requirements of the microgrid. Taking a CNCHP microgrid of an industrial park as an example, the correctness and validness of the proposed optimal calculation model are verified. The results show that the optimal operation scheme of the CNCHP microgrid can effectively reduce the operating cost and improve the energy efficiency.

Keywords: Combined natural gas, cooling, heating and power; Microgrid of an industrial park; Optimal energy flow calculation; integrated energy network.

INTRODUCTION

Combined natural gas, cooling, heating and power joint supply (CNCHP) park microgrid is an important aspect of the practical application of multi-energy complementary technologies. As an integrated energy system, a variety of energy sources such as electricity, gas, cold and heat are mutually coupled and interact with each other. The coordinated and optimized operation of multi-energy interconnection can effectively improve the economic and environmental benefits of the entire microgrid operation, and has been widely used in the energy supply of new industrial parks [1-2]. In the operation of CNCHP microgrid, the balance of various energies involves the coordinated operation of various types of energy supply equipment such as power supply, gas supply, cooling and heating. Therefore, it is necessary to describe the mathematical model of various energy supply devices in the

microgrid and establish its optimal energy flow calculation model, and calculate its optimal operation mode, which is of great significance for the development and application of the CNCHP microgrid as well as the efficient use of various energies.

At present, the research on multi-energy systems including CNCHP microgrid has aroused widespread concern, mainly focusing on the modeling and energy flow calculation of multi-energy systems [3-4], coordinated optimal planning and operation of multi-energy systems [5-8], etc. Among them, in the optimal operation of multi-energy system, reference[6] proposed a new sub-energy hub modeling structure, and established the optimal scheduling model of micro-energy network considering the thermal energy storage device and demand response model; reference[7] established a joint scheduling model with new energy, energy storage equipment and CCHP system, simulated the best output of each unit in the system, the total operating cost under different scheduling modes and the unit combination of gas turbine. In reference [8], considering the wind power and P2G process, a bi-level economic dispatching model of integrated natural gas and power system with security operation constraints is proposed: the upper level is the optimization model of power system and the lower level is the optimal distribution of natural gas system. The above references for the optimization of multi-energy system has the following deficiencies: the optimization model mostly adopts a common energy hub model, but does not consider the detailed network characteristics constraints in the heating, cooling and gas supply networks, which neglect the energy transmission loss, and makes the optimal results not accurate enough.

In this paper, the optimal energy flow calculation of the CNCHP microgrid is studied. Based on the detailed network characteristics constraints of electricity, gas, cold and heat, aimed at the minimum of operating cost, an optimal operation model of CNCHP microgrid is established. Taking a CNCHP microgrid of an industrial park as an example, the results verify the correctness of the proposed optimal calculation model and the economy of the optimal scheduling solution.

THE STRUCTURE OF CNCHP MICROGRID OF AN INDUSTRIAL PARK

The Structure of CNCHP microgrid is shown in Figure 1, including natural gas stations, gas generators, refrigeration equipment, heating equipment and power supply, air supply, heating and cooling network. As a cold and thermoelectric energy output, the energy station transforms the heat generated by natural gas into mechanical energy through gas turbines, internal combustion engines and other power generation equipment, and further converts it into electric energy to supply electricity to users. The insufficient electric load demand is supplemented by the distribution network. At the same time, it collects generator waste heat, such as high temperature flue gas, cylinder liner, hot water, etc., and then produces cold water and hot water through cooling equipment (such as smoke and hot water lithium bromide absorption chiller) and heating equipment, such as heat exchanger, to provide cooling and heating to users. The insufficient demand for cold load is supplemented by electric refrigerators, and the insufficient heat load demand is supplemented by electric heating boilers and gas fired boilers.

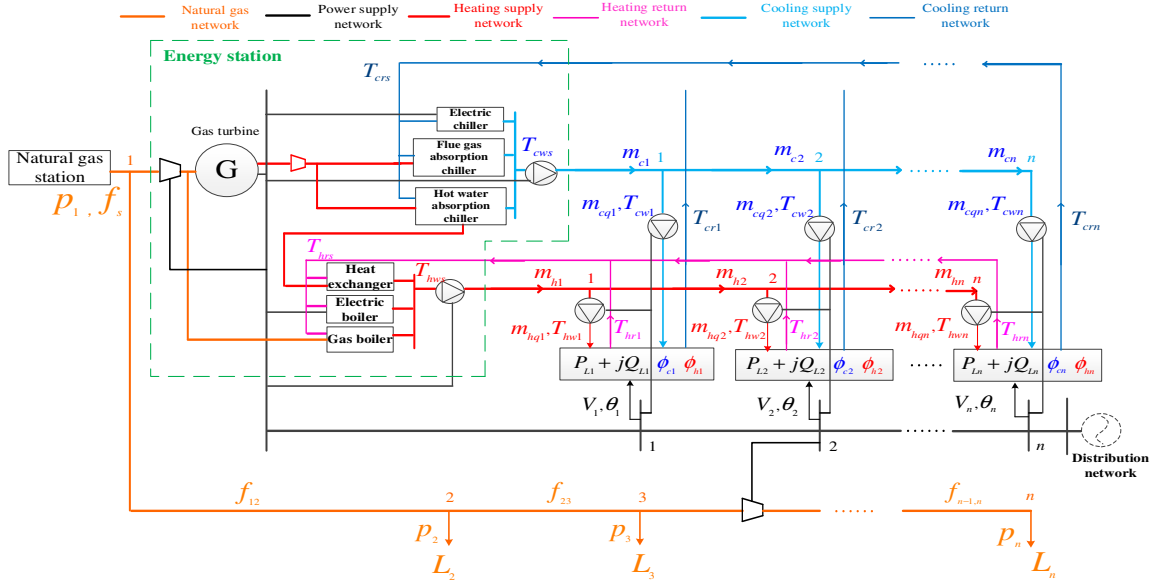


Figure 1. Structure diagram of CNCHP microgrid.

MATHEMATICAL MODEL OF OPTIMAL ENERGY FLOW CALCULATION OF CNCHP MICROGRID

The Objective Function

The mathematical model takes the minimum total running cost of the microgrid as the objective function, including the purchase cost of the microgrid from the natural gas station and the purchase cost of the power distribution network, as shown in formula (1) [9].

$$\min f(x) = c_{gas} f_s + c_{grid} P_{grid} \quad (1)$$

Where, c_{gas} is the unit price of natural gas, f_s is the gas flow injected into the microgrid from the natural gas station, c_{grid} is the unit price of the electricity purchased from the distribution network, and P_{grid} is the active power injected into the microgrid of the distribution network.

Restrictions

1) Operating Characteristic Constraints of the Cooling / Heat Network

The operating characteristic constraints of cooling /heat Network include the thermodynamic model of the fan coil /heat exchanger for the cooling / heat load node, temperature drop and temperature rise model of water supply pipeline, pipeline fluid in the node mass mixing model and the temperature model, power consumption model of circulating water pump in the network, which are shown in formula (2).

$$\begin{cases} \phi_j = c_w m_{qj} s_j (T_{rj} - T_{wj}) \\ T_{op} = (T_{ip} - T_a) e^{-\lambda L / (c_w m_j)} + T_a \\ \sum m_{in} = \sum m_{out} \\ \sum (m_{in} T_{in}) = (\sum m_{out}) T_{out} \\ P_{pj} = m_j g H / (\rho_w \eta_p) \end{cases} \quad (2)$$

Where, ϕ_j is the load power of the fan coil/heat exchanger, c_w is the specific heat capacity of water, m_{qj} is the flow of cold /hot water flowing through the fan coil/heat exchanger, s_j is used to characterize the load at node j , taking +1 for the coil and -1 for the heat load exchanger; T_{wj} and T_{rj} are the fan coil /heat exchanger inlet temperature and return water temperature respectively. T_{op} is the outlet water temperature of the pipeline, T_{ip} is the inlet water temperature of the pipeline, T_a is the ambient temperature, λ is the heat transfer coefficient per unit length of pipe, L is the pipeline length. m_{in} and m_{out} are the fluid flows into and out of the nodes, T_{in} and T_{out} are the temperature of each fluid flowing into the node before mixing and the temperature of the fluid flowing out of the node after mixing. P_{pj} is the circulating pump power consumption under the conditions of use, g is the acceleration of gravity, ρ_w is the density of water, η_p is the efficiency of water pump, H is the head of the pump.

2) Operating Characteristic Constraints of the Gas Supply Network

The operation characteristics constraints of the gas supply network include the relationship between the pipe flow rate and gas pressure at both ends under steady-state conditions and the power consumption model of the electrically-driven compressor in the network, which are shown in formula (3).

$$\begin{cases} f_{ij} = K_{ij} s_{ij} \sqrt{s_{ij} (p_i^2 - p_j^2)} \\ HP = \frac{p_{in} f_{in} \alpha}{\eta (\alpha - 1)} [(p_{out} / p_{in})^{\frac{\alpha-1}{\alpha}} - 1] \end{cases} \quad (3)$$

Where, f_{ij} is the flow through the pipe from node i to j , K_{ij} is the pipe constant, p_i 、 p_j are the pressure at nodes i and j , s_{ij} is used to characterize the flow of natural gas, +1 for $p_i > p_j$, and -1 otherwise; HP is the electrical power consumed by the electrically driven compressor, p_{in} and p_{out} are the inlet and outlet pressures of the compressor, f_{in} is the inlet flow, η is the compressor efficiency, and α is the variable index.

3) Operating Characteristic Constraints of the Power Supply Network

In the operation characteristic constraints model of the power supply network, the power consumed by each electric load node considers the electric power consumed by the circulating water pump at the cooling /heating network load side and the compressor at the load side of the gas supply network, as shown in formula (4). And reactive balance equation is shown in formula (5).

$$P_{Lj} + jQ_{Lj} = (P_j + P_{pcj} + P_{phj} + HP_j) + j(Q_j + P_{pcj} \tan \phi_{cj} + P_{phj} \tan \phi_{hj} + HP_j \tan \phi_{hpj}) \quad (4)$$

Where, P_j and Q_j are the active and reactive powers of the load node j without considering the power consumption of circulating pump and compressor, P_{pcj} and P_{phj} are the electric power consumed by the circulating pump on the cooling and heat load side, ϕ_{cj} and ϕ_{hj} are power factor angle of the circulation pump of cooling load side and the heat load side, ϕ_{hpj} is the power factor angle of supply network compressor.

$$\begin{cases} P_{sj} - P_{Lj} - V_j \sum_{i=1}^n V_i (G_{ji} \cos \theta_{ji} + B_{ji} \sin \theta_{ji}) = 0 \\ Q_{sj} - Q_{Lj} - V_j \sum_{i=1}^n V_i (G_{ji} \sin \theta_{ji} - B_{ji} \cos \theta_{ji}) = 0 \end{cases} \quad (5)$$

Where, for the contact node between the microgrid and the distribution network, $P_{sj} = P_{grid}$, $Q_{sj} = Q_{grid}$, Q_{grid} is the reactive power injected into the microgrid for the distribution network, $P_{sj} = 0$, $Q_{sj} = 0$ for other nodes. V_j is the voltage amplitude of node j , G_{ij} and B_{ij} are the conductances and susceptances of the line between nodes i and j , and θ_{ij} is the phase difference between the voltages of nodes i and j .

4) Operating Characteristics Constraints of the Energy Station

The operating characteristics constraints of the energy station include the energy conversion model of the natural gas CHP unit, the energy conversion model of the absorption chiller, the electric cooler, the heat exchanger, the electric boiler and the gas boiler, and the balance equation of the various energy supply in the energy station.

The relationship between the efficiency of a gas turbine and its total active output is described by a cubic model as shown in formula (6)[10].

$$\eta_G = a + bP_G^* + c(P_G^*)^2 + d(P_G^*)^3 \quad (6)$$

Where, η_G is the efficiency of the gas turbine, a , b , c and d are the efficiency coefficient of the gas turbine generator, P_G^* is the ratio of the total active power of the gas turbine P_G to the rated active power.

According to the power generation efficiency and the power generation power, the thermal power of the natural gas consumed by the gas turbine generator Q_{fuel} can be calculated as shown in formula (7). After deducting the power of generation, it turns into the emission power of the waste heat, and the heat input power of the hot water type absorption chiller Q_{water} and the flue gas absorption chiller Q_{smoke} can be further calculated as shown in formula (8) and (9). α_{water} is the waste heat factor of the cylinder liner water and α_{smoke} is the waste heat factor of the flue gas.

$$Q_{fuel} = P_G / \eta_G \quad (7)$$

$$\phi_{water} = \alpha_{water} (Q_{fuel} - P_G) \quad (8)$$

$$\phi_{smoke} = \alpha_{smoke} (Q_{fuel} - P_G) \quad (9)$$

For the cooling units, the hot water absorption chiller and the flue gas absorption chiller use the high temperature cylinder liner and the exhaust gas to refrigerate respectively. The electric refrigerator is powered by electric energy. And the refrigeration powers are respectively shown in formula (10).

$$\begin{cases} \phi_{c1} = COP_1 \cdot \phi_{water} \cdot \eta_{hrs1} \\ \phi_{c2} = COP_2 \cdot \phi_{smoke} \cdot \eta_{hrs2} \\ \phi_{c3} = COP_3 \cdot P_C \end{cases} \quad (10)$$

Where, ϕ_{c1} , ϕ_{c2} and ϕ_{c3} are the cooling power of the hot water absorption chiller and the flue gas absorption chiller and the electric chiller respectively, COP_1 , COP_2 and COP_3 are the thermal coefficients of the corresponding chillers, η_{hrs1} and η_{hrs2} are the efficiency of hot water and flue gas recovery, P_C is the electric power consumed by the electric chiller.

For the heating units, the heat exchanger makes heat by recovering the low temperature cylinder water from the hot water absorption chiller. And the electric heating boiler and the gas-fired boiler use electric energy and natural gas to make heat. The heating powers are respectively shown in formula (11).

$$\begin{cases} \phi_{h1} = \eta_{hrs3} \phi_{water} (1 - \eta_{hrs1}) \\ \phi_{h2} = \eta_H \cdot P_H \\ \phi_{h3} = \eta_g \cdot f_H \cdot q_{LNG} \end{cases} \quad (11)$$

Where, ϕ_{h1} , ϕ_{h2} and ϕ_{h3} are the heating power of the heat exchanger unit, electric boiler and gas boiler respectively, η_{hrs3} is the efficiency of the heat exchanger, η_H and η_g are the efficiencies of the electric boiler and the gas boiler respectively, P_H is the electric power consumed by an electric heating boiler, f_H is the natural gas flow consumed by the gas boiler heating, q_{LNG} is the natural gas calorific value.

The cooling/heating balance inside the energy station is described as formula (12).

$$\begin{cases} \phi_{ctotal} = N_1 \phi_{c1} + N_2 \phi_{c2} + \phi_{c3} \\ \phi_{htotal} = N_w \phi_{h1} + \phi_{h2} + \phi_{h3} \end{cases} \quad (12)$$

Where, ϕ_{ctotal} and ϕ_{htotal} are the total cooling load and heat load requirements, N_1 and N_2 are the number of cooling units for flue gas and hot water absorption chillers, and N_w is the number of heating units for heat exchanger.

The balance of active and reactive power in the internal power supply section of the energy station, that is, the power balance equation of the generator bus terminal of the gas turbine is described as Formula (13).

$$\begin{cases} P_G - (P_{phs} + P_{pcs} + HP_s + P_C + N_1 P_{c1} + N_2 P_{c2} + N_w P_w + P_H) - V_k \sum_{j=1}^n V_j (G_{kj} \cos \theta_{kj} + B_{kj} \sin \theta_{kj}) = 0 \\ Q_G - (P_{phs} \tan \varphi_{phs} + P_{pcs} \tan \varphi_{pcs} + HP_s \tan \varphi_{hps}) - V_k \sum_{j=1}^n V_j (G_{kj} \sin \theta_{kj} - B_{kj} \cos \theta_{kj}) = 0 \end{cases} \quad (13)$$

Where, P_{c1} , P_{c2} , and P_w are the electric power consumed by a single flue gas type, hot water type absorption chiller and heat exchange unit, Q_G is the reactive power output of the gas generator.

In the part of the gas supply network inside the energy station, the gas consumption consumed by the gas generator and the gas boiler together constitutes the gas load L at the node of the natural gas network at the energy station, which is shown in formula (14).

$$L = Q_{fuel} / q_{LNG} + f_H \quad (14)$$

5) Upper and Lower Bound Constraints of Variables

Constraints on system variables include upper and lower limits of grid node voltage magnitude, upper and lower limits of heating / cooling network pipeline flow, upper and lower limits of pipeline pressure of natural gas grid, and upper and lower limits of each equipment variable of energy station (including active and inactive output of gas generator, Absorption chiller and heat exchanger units into the number of electric chiller electric boiler and gas boiler input power, etc.).

$$x_{\min} \leq x \leq x_{\max} \quad (15)$$

Formula (1) to formula (15) constitute the optimal energy flow calculation model for CNCHP microgrid. Since the decision variables in the model include discrete variables of the absorption chiller and the number of input units of the heat exchanger unit, the optimization model is a mixed integer nonlinear programming model, which can be solved by using the SBB solver in GAMS software.

CASE STUDIES

Taking a CNCHP microgrid of an industrial park as an example, the wiring diagram is shown in Figure 2. Among them, the cooling network and the heating network include 13 nodes and 12 sections of pipelines; the gas supply network includes 9 nodes and 6 sections of pipelines; and the power supply network includes 54 nodes and 78 branches. The computer used for optimization calculations is Intel (R) Xeon (R) CPU E3-1270 3.60 GHz with 32 GB of memory.

P_G (MW)	P_{grid} (MW)	Q_G (MVar)	Q_{grid} (MVar)	$f(x)$ (yuan)
4	15.78	42.76	5.96	57109.95

Table II. The variable values of the generator and the grid node under the optimal solution.

N_1	N_2	$N_1 P_{c1}$ (kW)	$N_2 P_{c2}$ (kW)	ϕ_{c1} (MW)	ϕ_{c2} (MW)	P_C (kW)	ϕ_{c3} (MW)
5	5	750	600	18.96	14.32	2280	11.40

Table III. The value of the variable on the cooling side under the optimal solution.

N_w	$N_w P_w$ (kW)	ϕ_{h1} (MW)	P_H (kW)	ϕ_{h2} (MW)	ϕ_{h3} (MW)
5	600	12.27	2880	2.30	6.45

Table IV. The value of the variable on the heating side under the optimal solution.

Table 5 shows the power consumption ratio of each power equipment in the energy station. It can be seen that in addition to electric refrigerators and electric heating boilers, the cooling/heating water pump and natural gas compressor share a total of 58% of the power consumption, consuming a large amount of electricity. Therefore, the detailed modeling in the energy station is beneficial to the more accurate calculation of the energy flow.

Absorption chillers(%)	Heat exchange(%)	Electric chiller(%)	Electric boiler(%)	Cooling / heating water pump(%)	Natural gas compressor(%)
8	3	13	17	23	35

Table V. Proportion diagram of each power consumption equipment inside the energy station.

Before optimization, suppose that the grid and energy station each run on a fixed scheme with half the power demand, and the results of calculating the micro-grid energy flow are shown in Tables 6 to 8. It can be seen that the operating cost of a fixed proportional scheme by increasing the distribution ratio of power distribution network is 16.47% higher than that of the optimal scheme. There are two reasons for this: 1) As the cost of power generation by gas turbine in energy station is cheaper than the purchase of power from distribution network, when the proportion of power supply load in distribution network increases, the operating cost of micro-grid also becomes larger. 2) When the active output of the gas generator of the energy station is reduced, the input power of the absorption chiller and the heat exchange unit is reduced, resulting in the reduction of the cooling supply of the two chiller units and the heat supply of the heat exchanger units, In the cooling side, the input power of the electric chiller should be increased so as to meet the cooling demand, while the heating side, due to the output power of the gas boiler the limit, so it is necessary to increase the input power of electric boiler to meet the heating demand.

P_G (MW)	P_{grid} (MW)	Q_G (MVar)	Q_{grid} (MVar)	$f(x)$ (yuan)
43.5	30.18	40.04	7.14	66516.15

Table VI. The variable values of the generator and the grid node under the fixed solution.

N_1	N_2	$N_1 P_{c1}(\text{kW})$	$N_2 P_{c2}(\text{kW})$	ϕ_{c1} (MW)	ϕ_{c2} (MW)	P_c (kW)	ϕ_{c3} (MW)
5	5	750	600	16.08	12.14	3240	16.20

Table VII. The value of the variable on the cooling side under the fixed solution.

N	$N_w P_w$ (kW)	ϕ_{h1} (MW)	P_H (kW)	ϕ_{h2} (MW)	ϕ_{h3} (MW)
5	600	10.41	5220	4.18	6.45

Table VIII. The value of the variable on the cooling side under the fixed solution.

CONCLUSION

Based on the detailed constraints of network characteristics of electricity, gas, cold and heat, this paper establishes an optimal energy flow calculation model of CNCHP microgrid with the objective of minimizing the operating cost. The feasibility of the optimization model and the economy of the optimization scheme are verified through an example analysis, and the following conclusions are obtained:

1) Due to the restriction of the network characteristics of electricity, gas, cold and heat, the model of CNCHP microgrid can consider the loss of each type of network, as well as the power consumption of the cooling /hot water pump and the natural gas compressor, which is beneficial to the more accurate calculation of the optimal energy flow.

2) The obtained optimal operation scheme of solving the optimal energy flow calculation model of CNCHP microgrid has better economic performance than the operation scheme in which the power grid and the energy stations undertake the fixed active power output.

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