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MULTI-OBJECTIVE CONFIGURATION OPTIMIZATION OF DCCHP SYSTEM BY NSGA-II

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ABSTRACT

Owing to the limitation of single objective optimization configuration of the distributed combined cooling heating and power (DCCHP) system, the multi-objective optimization configuration of the system was carried out from the aspects of energy efficiency and economy. Taking the maximum primary energy saving (PES) and minimum annual cost (AC) as the objective functions, three key parameters of gas turbine capacity, absorption refrigeration ratio and gas turbine minimum load rate were selected as decision variables. Non-dominated sorting genetic algorithm II (NSGA-II) was used to optimize the system with multi-objective, and subsequently Pareto optimal solutions were obtained. With the aid of ideal point method, the optimal capacity configuration of the system was selected. For the case of an energy supply system of a hotel, optimized results show that under the given parameters, the optimal PES is 0.6788 and the minimum AC is 2.1309 million yuan in consideration of both energy efficiency and economy.

Keywords: Distributed combined cooling heating and power, multi-objective optimization, non-dominated sorting genetic algorithm

1. INTRODUCTION

Distributed combined cooling heating and power (DCCHP) system is defined as a power supply system built on or near the user side, which can simultaneously provide cold, heat and electricity. With the wide application of DCCHP system, how to optimize the configuration of each equipment capacity is one of the key points of the system design[1].

Most of the optimization studies only considered energy efficiency or economy unilaterally, and obtained the equipment capacity configuration results when the system achieves the best energy efficiency or economy[2-5]. In addition, some studies used the method of weight factor to transform multi-objective into single-objective optimization, which is still a single-objective optimization[6-8]. In the actual system equipment capacity configuration, single-objective optimal configuration often fails to meet the design requirements, and the improvement of the system energy efficiency often leads to economic deterioration. Therefore, it is necessary to take into account a variety of factors to optimize the configuration of DCCHP system with multiple objectives.

2. MULTI-OBJECTIVE OPTIMIZATION MODEL OF DCCHP SYSTEM

Different DCCHP systems have various components. Selecting what kind of components depends on the application scenarios, such as the island, the hotel, the industrial park, etc. For example, the DCCHP system employed by the hotel is shown in Fig. 1. Electricity is provided by the gas turbine (GT) and local utility grid. The waste heat is recovered in the heat recovery system and used to produce cooling by absorption chiller or heating by heating exchanger to meet the heat demands. A supplementary boiler is used to replenish heat if the recovered heat is not sufficient. The cooling demand of buildings is satisfied by the absorption chiller and electric chiller.

The mathematical model the GT is as follows:

$$\eta_{\mathrm{GT}}^{\mathrm{E}} = aL^3 + bL^2 + cL + d \quad (1)$$

$$\eta_{\mathrm{GT}}^{\mathrm{H}} = eL^3 + fL^2 + gL + h \quad (2)$$

where $\eta_{\mathrm{GT}}^{\mathrm{E}}$ is the generation efficiency of GT, $\eta_{\mathrm{GT}}^{\mathrm{H}}$ is the thermal efficiency of GT, *a, b ,c, d, e, f and g* are the efficiency parameters, *L* is the load rate.

The mathematical model the absorption chiller is as follows:

$$Q_{AC}=Q_{AC}^{R}\cdot L_{AC}=Q_{ha}\cdot COP_{AC} \tag{3}$$

$$COP_{AC}=a_{AC}\cdot L_{AC}^{3}+b_{AC}\cdot L_{AC}^{2}+c_{AC}\cdot PLR_{AC}+d_{AC} \tag{4}$$

where Q_{AC} is the cold power output of absorption chiller; Q_{ha} is the thermal power input of absorption chiller; COP_{AC} is the refrigeration performance coefficient of absorption chiller. a_{AC}, b_{AC} ,c_{AC} *and* d_{AC} *are* the efficiency parameters. L_{AC} is the load rate.

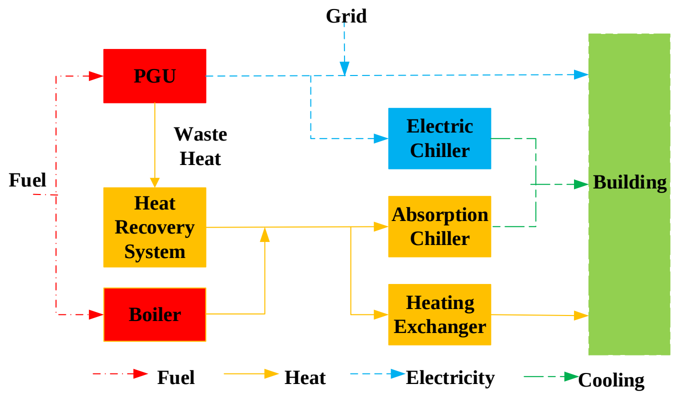


Figure 1 Schematic of the typical DCCHP system

2.1 Objective functions and optimization variables

Choosing the primary energy saving (PES) and annual cost (AC) as objective functions from two aspects of energy efficiency and economy. The PES and AC can be expressed as the following equations:

$$\mathrm{PES}=\frac{E+Q_{C}+Q_{H}}{F} \tag{5}$$

$$\mathrm{AC}=R\cdot\sum_{i}P_{i}N_{i}+\sum_{\mathrm{hour}}\left(V_{gas}u_{gas}+E_{grid}u_{grid}\right) \tag{6}$$

where E is the electricity consumed by users, Q_C is the cooling demand, Q_H is the heating demand, F is the total energy consumption, i is the type of equipment, P_i is the capital cost of equipment, N_i is the nominal capacity, V_{gas} and E_{grid} are the consumption of natural gas and grid electricity, respectively. u_{gas} and u_{grid} are the hourly charge of natural gas and grid electricity, respectively. R is specified in the following equations.

$$R=\frac{i_{0}\cdot(1+i_{0})^{n}}{(1+i_{0})^{n}-1} \tag{7}$$

where i_0 is the interest rate, n is the service life of equipment. It is assumed that all types of equipment have the same value of i_0 and n.

Three key parameters affecting system configuration results are selected as decision variables, namely, gas turbine capacity N_{pgu}, absorption refrigeration ratio β and gas turbine minimum load rate L. When PES and AC are selected as objective functions, PES is required to be the largest while AC is the smallest, as follows:

$$\begin{cases}\max.PER\left(N_{pgu},\beta,L\right)\\ \min.AC\left(N_{pgu},\beta,L\right)\end{cases} \tag{8}$$

The constraints of multi-objective optimization are as follows:

$$E_{dmn}=E+E_{EC}\le E_{pgu}+E_{grid} \tag{9}$$

$$Q_{H,dmn}=Q_{H}+Q_{H,AC}\le Q_{H,RE}+Q_{H,GB} \tag{10}$$

$$Q_{C,dmn}=Q_{C}\le Q_{C,AC}+Q_{C,EC} \tag{11}$$

where E_{dmn} is the total electricity demand, E_{EC} is the electricity consumed by electric chiller, E_{pgu} is the gas turbine power generation, E_{grid} is the purchased power. $Q_{H,dmn}$ is the total heating demand, $Q_{H,AC}$ is the heating consumed by absorption chiller, $Q_{H,RE}$ is the heating supplied by heat recovery system, $Q_{H,GB}$ is the heating supplied by supplementary boiler. $Q_{C,dmn}$ is the total cooling demand, $Q_{C,AC}$ is the cooling supplied by absorption chiller, $Q_{C,EC}$ is the cooling supplied by electric chiller.

2.2 Optimization method

Configuration optimization of DCCHP system is a multi-objective problem. In this paper, Non-dominated sorting genetic algorithm II (NSGA-II) is used to solve the problem. NSGA-II is a multi-objective genetic algorithm with strong variable processing ability and global optimization ability, which can maximize the independence between the optimization objectives. The process of NSGA-II is as follows:

(1) Initial population P_0 is generated randomly, and the size of population is N. The offspring population Q_0 is generated by crossover and mutation operation.

(2) Combining the parent population with the offspring population into a new population R_t.

(3) The population R_t was sorted by non-dominant ranking, which was divided into different non-dominant ranks F_1, F_2, etc.

(4) The new population is filled by individuals with different non-dominant front-end, in order of F_1, F_2 ,etc. Selecting the remaining positions in the filling population with large crowding distance, and form a new population P_{t+1}.

(5) The crossover and mutation of population P_{t+1} were carried out to form population Q_{t+1}.

(6) If the termination condition holds, it ends, otherwise, jump to step (2).

The main process of the algorithm is shown in Fig. 2.

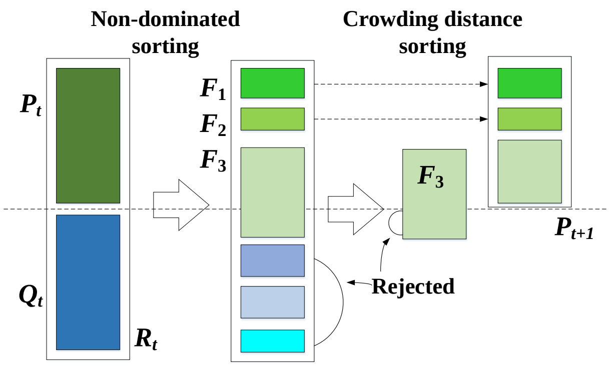


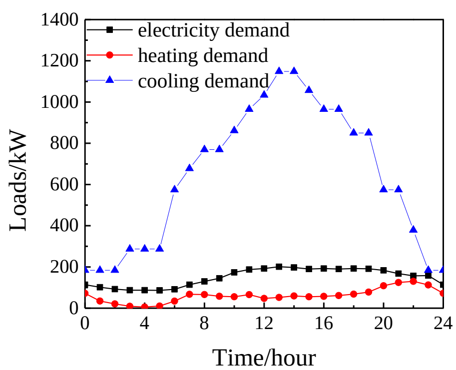
Figure 2 NSGA-II procedure

3. CASE STUDY

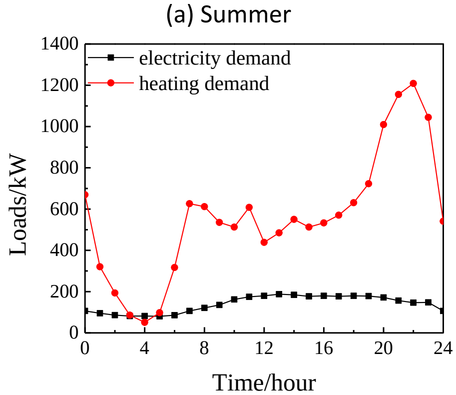
3.1 Load demand and related parameter setting

The optimization model is applied to the energy supply system design of a hotel in Xi'an, China. The typical day load demand of the hotel is shown in Fig. 3.

The price of natural gas in Xi'an is 2.3 yuan/Nm^3, and the hourly electricity price is shown in Table 1. The economic and technical parameters of equipment in DCCHP system are listed in Table 2. The GA parameters are listed in Table 3.



(a) Summer



(b) Winter

Figure 3 Heating, cooling, and electricity demands of the hotel for typical day

Considering that in actual operation, the efficiency of GT will have obvious impact on the performance of the power supply system with the load change. Therefore, the following fitting formulas are used to express the relationship between the generation efficiency, thermal efficiency and load rate of GT, respectively:

$$\eta_{GT}^{E} = 0.1283L^3 - 0.6592L^2 + 0.7945L + 0.003 \quad (12)$$

$$\eta_{GT}^{H} = -0.7098L^3 + 1.5206L^2 - 1.1191L + 0.835 \quad (13)$$

Table 1 hourly electricity price

Time interval	Time/h	Price/yuan·(kW·h)$^{-1}$
8:00~11:00 18:30~23:30	8	1.1698
23:30~7:00	7.5	0.4172
11:00~18:30 7:00~8:00	8.5	0.7934

Table 2 economic and technical parameters of equipment

Item	Value	Unit
Generating efficiency of GT	——	
Waste heat efficiency of GT	——	
Coefficient of performance of electric chiller	4.0	
Coefficient of performance of absorption chiller	1.1	
Efficiency of heat recovery system	0.9	
Efficiency of boiler	0.85	
Efficiency of heating exchanger	0.9	
Unit price of GT	8000	yuan/kW
Unit price of electric chiller	970	yuan/kW
Unit price of absorption chiller	1200	yuan/kW
Unit price of heat recovery system	851	yuan/kW
Unit price of boiler	851	yuan/kW
Unit price of heating exchanger	200	yuan/kW

Table 3 GA Parameters

Item	Value
Population Size	200
ParetoFraction	0.3
Crossover Fraction	0.7
Generations	150
EliteCount	10

3.2 Results and discussion

Figure 4 shows the optimal solution (Pareto optimal frontier) of the multi-objective optimization system using NSGA-II. How to choose a suitable solution to meet the requirements of optimal design in multi-objective optimization solution set is a problem that must be solved in multi-objective optimization.

For multi-objective optimization of DCCHP system, it is to select a more appropriate solution from the Pareto optimal solution in search space, so that the comprehensive performance of the system is the best. Selecting the optimal solution is a decision-making process. In fact, the decision-making process mainly depends on engineering experience and preferences of decision makers. In this paper, an ideal point C at which each single objective function achieves its optimal value were assumed, and two objective functions cannot achieve the optimal value at the same time, as shown in Fig. 5. Then, the shortest distance from the ideal point (point C) to the Pareto optimal frontier is obtained to get the F point.

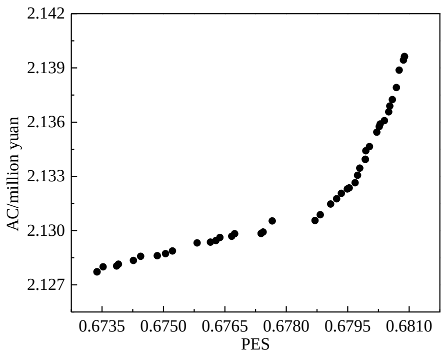


Figure 4 Pareto optimal solutions

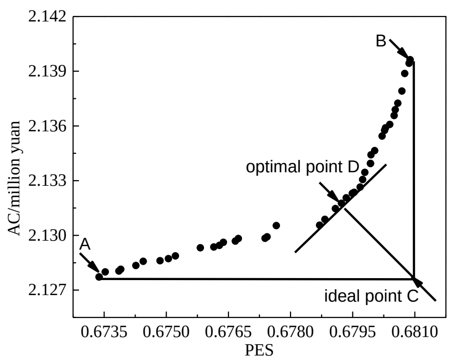


Figure 5 Selection of optimal solution from the Pareto Frontier

Table 4 shows the objective value of the optimal solution of Pareto's optimal frontier. Point F is the final optimal solution. The PES of the system is 0.6788, and the AC of the system is 2.1309 million yuan. Table 5 shows the corresponding equipment capacity of DCCHP system.

Tab 4 The target value of the Pareto optimal frontier

Item	A	B	F
PES	0.6733	0.6809	0.6788
AC (million yuan)	2.1277	2.1396	2.1309

Table 5 Equipment capacity of DCCHP system

Item	Capacity/kW
GT	267
electric chiller	339
absorption chiller	809
heat recovery system	475
boiler	1006
heating exchanger	1209

4. CONCLUSION

Taking the maximum PES and minimum AC as objective functions, the multi-objective optimization design of DCCHP system was carried out by using NSGA-II, and the Pareto optimal solution set was obtained. The suitable multi-objective optimization solution was selected by ideal point method. For the case of an energy supply system of a hotel, the PES of the system was 0.6788, and the AC is 2.1309 million yuan.

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