Optimal Operation of a Trigeneration System Based on Gas-Steam Combined Cycle

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Abstract. In order to save the energy of the trigeneration system based on gas-steam combined cycle, this paper proposes to explore optimal operation modes related to primary energy saving (PES) and operating costing saving (OCS) respectively, by considering the parallel operation of the gas turbine and the steam turbine valve. By taking the summer load of an office building group as the research object, the variations of controllable parameters and indexes are analysed in the trigeneration system with the traditional operation mode and the optimal operation modes. The results suggest that the proposed two operation modes over energy saving and economic aspects are more appropriate than the traditional modes.

1 Introduction

A trigeneration system (TS) could involve multiple inputs and outputs. How to meet the demand is an important question for a trigeneration system. There are many selective operation modes of trigeneration systems. Appropriate operation mode can improve the performance of trigeneration system. Moreover, consumption of fuel and pollutant emissions can be reduced in appropriate operation mode. At present, there are two typical operation modes for trigeneration system as follows:

(1) following the electric load [1]. The system gives priority to meet the external electric load, and the insufficient heat load is supplemented by gas boiler or other heating methods;

(2) following the thermal load. The system gives priority to generate enough heat to meet the external thermal load or the colding load, and the insufficient electric load are supplemented by the public electric grid or other power supply methods.

Above two modes sometimes produce incompatible heat or electricity [2]. Therefore, some efforts have been made to improve the two operation modes. The literature [3] analysed the influence of two operation modes on primary energy consumption, operation cost and carbon dioxide emission in different conditions, and it concluded that adjusting the two operation modes can improve the operation performance of a system.

In the scenario of peak-to-valley electricity price, this paper constructs a combined cooling and heating power supply system based on gas-steam combined cycle and establishes its characteristic model. Firstly, based on the primary energy saving (PES) and operating cost saving (OCS), the particle swarm algorithm (PSO) is used to

formulate two operational strategies to meet the load situation of the buildings group. In the load situation of a typical summer day, through the variations of controllable parameters, the indexes in the trigeneration system in these two operating modes, i.e., the following the electric load and following the thermal load, are then compared with the results of the traditional modes. The results verify the superiority of these two strategies.

The rest of this paper is organized as follows. Section 2 and 3 recall the trigeneration system based on gas-steam combined cycle. Section 4 presents the optimal model and results are shown in Section 5. The last section concludes this paper.

2 A trigeneration System Based on Gas-Steam Combined Cycle

The trigeneration system considered in this paper, as shown in Figure 1, consists of gas turbines (GT), dual-pressure HRSG, single extraction condensing steam turbine (ST), lithium bromide refrigerator (LBR), compression refrigerator, gas boiler, and heat recovery unit (HRU). It can be seen from Figure 1 that the gas turbine, HRSG and steam turbine adopt the two-to-one operation mode, i.e., the two sets of gas turbine-HRSG and one steam turbine are connected. This paper assumes that the characteristics of two gas turbines and two HRSG are the same.

Natural gas is burned in a gas turbine, and exhaust gas is obtained after power generation. The exhausted gas gets into the HRSG which transfer the heat from the exhausted gas to the water, and the water is heated into the high-pressure steam, low-pressure steam, and hot water. The high-pressure steam gets into the steam

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turbine to generate power. The low-pressure steam and extraction steam from the ST are used as the drive

thermal resource for the absorption chiller. The hot water is used to supply the heat.

Figure 1. Schematic Diagram of Trigeneration System.

3 Establishing the model of the equipments

3.1 Modelling of Gas turbine

The trigeneration system use LM2500+G4 as gas turbine. From the manufacturer's design data, the linear relationship between the power generated and the fuel is

$$P_{e_{gt}} = 21.74 \cdot G_{f_{gt}} - 8.90 \quad (1)$$

where $G_{f_{gt}}$ is the flow rate of the gas fuel, $P_{e_{gt}}$ is the electricity generated by gas turbine.

3.2 Modelling of HRSG

The dual-pressure HRSG uses the residual heat of the gas turbine exhaust to generate high-pressure or low-pressure steam. From the design data of the HRSG and GT, the high-pressure steam generated by HRSG is showed as

$$Q_{HPS} = (4.92 \times G_{f_{gt}} + 2.17) \cdot \Delta h_{HPS} \quad (2)$$

The low-pressure steam generated by HRSG is showed as

$$Q_{LPS} = (-0.62 \times G_{f_{gt}}^2 + 2.56 \times G_{f_{gt}} - 0.45) \cdot \Delta h_{LPS} \quad (3)$$

Where Q_{HPS} , Q_{LPS} , Q_{water} are the heat of high-pressure steam, low-pressure steam and hot water respectively. Δh_{HPS} , Δh_{LPS} , Δh_{HPS} are the difference of the enthalpy between the outlet of HRSG and the back water respectively.

3.3 Modelling of steam turbine

The condensing steam turbines generate electricity and provide a certain amount of heat using high-pressure steam of the HRSG. Power generation is related to the flow of high-pressure steam and the flow of extracted steam. The power generated by the turbine is

$$P_{e_{st}} = D_{HPS} \cdot (h_0 - h_c) - \alpha \cdot D_{HPS} \cdot (h_{ex} - h_c) \quad (4)$$

the heat of steam turbine is

$$Q_{ex} = \alpha \cdot D_{HPS} \cdot (h_{ex} - h_{bw}) \quad (5)$$

where the $P_{e_{st}}$ is the power generated by the steam turbine, Q_{ex} is the heat provided by the extraction steam. D_{HPS} is the flow of the high-pressure steam, α is the extraction ratio of the flow of extraction to the flow of main steam in the ST, and h_0 , h_c , h_{ex} , h_{bw} is the enthalpy of the main steam of ST, exhausted steam, extraction steam, and back water respectively.

3.4 Other models

In the trigeneration system, there are the absorption chiller, the compression electric chiller, heat exchanger, and gas boiler. Those equipments use linear models in this paper, assuming that the efficiency of each equipment is constant.

4 Procedure of optimization

4.1 The objectived of optimization

4.1.1. Primary Energy Consumption (PES) Primary Energy Consumption (PEC) refers to the amount of fuel consumed by the trigeneration system and the amount of purchased electricity converted into standard primary energy consumption by conversion factor.

The primary energy energy consumption of the trigeneration system is defined as follows:

$$PEC_{TS} = P_{e_{grid}} / \eta_{grid} / \eta_{plant} + (G_{f_{gt}} + G_{f_b}) \quad (6)$$

In the formula, PEC_{TS} refers to PEC of the trigeneration system. η_{grid} and η_{plant} refer to the efficiency of grid electricity, 0.95, and the coal-fired power plant, 0.35, respectively.

In order to analyze the changes of the indicators before and after the operation of the trigeneration system intuitively, the primary energy consumption rate is selected as the optimization target and evaluation index of the trigeneration system, which is defined as the ratio of the difference between the PEC of the separate system (SS) and the trigeneration system to the PEC of the separate system. The definition is as follows:

$$PES = \frac{PEC_{ss} - PEC_{TS}}{PEC_{ss}} = 1 - \frac{PEC_{TS}}{PEC_{ss}} \quad (7)$$

The PES in equation (7) represents the primary energy saving rate.

4.1.2. Operation Cost Saving Operating cost (OC) mainly consists of the power purchase cost of the public grid, the cost of natural gas consumed by gas turbines and gas boilers, and equipment maintenance costs. For the trigeneration system, the operating cost is

$$OC_{des} = C_{grid} \cdot E_{grid} + C_{fuel} \cdot F_{fuel} + \sum_{i=1}^n C_{ope_i} \cdot N_i \quad (8)$$

where the C_{grid} , C_{fuel} , C_{ope_i} are the cost of power from the public grid, the natural gas, and the maintenance of each equipment respectively. i represents different equipment, n is the number of the equipment, N_i is the output of different equipment.

Operation cost saving (OCS) is the reduction in operating cost of trigeneration system relative to separate system, and the OCS is

$$OCS = \frac{OC_{ss} - OC_{ts}}{OC_{ss}} \quad (9)$$

where the OC_{ss} and OC_{ts} indicate the operation cost of the separate system and the trigeneration system respectively.

4.2 General Constraints

The mass and energy balance are the constraints to consider, they are shown below.

$$G_{f_gt\min} < G_{f_gt} < G_{f_gt\max} \quad (10)$$

$$\alpha_{\min} < \alpha < \alpha_{\max} \quad (11)$$

$$\begin{cases} 0 \leq Q_{ac} \leq Q_{ac\max} \\ 0 \leq Q_h \leq Q_{h\max} \end{cases} \quad (12)$$

$$\begin{cases} Q_h \geq Q_{h_load} \\ Q_{ac} + Q_{ec} \geq Q_{c_load} \\ Pe_{st} + Pe_{gt} - Pe_{ec} + E_{grid} \geq E_{load} \end{cases} \quad (13)$$

The Eq.10 and Eq.11 ensure that the input is within reasonable range. The Eq.12 ensures that the output of LBR and HRU don't excess the maximum. The Eq.13 is to make the output of heating, cooling, and power those the trigeneration system generated to meet the load demand.

4.3 Solution flow with PSO

In this section, the PES and the OCS established in Section 3 are optimized aim. According to the particle swarm optimization (PSO) [4-6], the load of a typical office buildings group in summer is optimized at a day, obtaining the strategy under the optimal operation mode.

The fuel consumption of the gas turbine and proportion of extraction steam are selected as decision variables, and m numbers of random individuals are

created, each of which includes a two-dimensional position vector and a two-dimensional velocity vector. The position vector of an individual could be

$$\bar{p}_j = (x_{j1}, x_{j2}) \quad (14)$$

Where x indicates the position in the dimension.

The velocity vector of an individual could be

$$\bar{v}_i = (v_{i1}, v_{i2}) \quad (15)$$

Where v indicates the velocity in the dimension.

The individuals are a population. After initializing the position and speed of the population, the corresponding fitness function is calculated according to different supplementary steam parameters, and the value of the supplementary steam parameter is determined according to the size of the fitness function, so that the continuous decision variable and integer decision can be decoupled.

The fitness function is a function of the particle position vector [7]. The fitness function can be expressed as:

$$fitness_i = f(\bar{x}_i) \quad (16)$$

The variables are decoupled, and the optimal position is determined according to global extremum.

$$\bar{p}_g = (p_{g1}, p_{g2}, p_{g3} \cdots p_{gd}) \quad (17)$$

The position and speed of the decision variables are updated.

$$\begin{cases} \bar{v}_i^{k+1} = \omega \cdot \bar{v}_i^k + c_1 \cdot r_1 \cdot (\bar{p}_j - \bar{x}_i^k) + c_2 \cdot r_2 \cdot (\bar{p}_g - \bar{x}_i^k) \\ \bar{x}_i^{k+1} = \bar{x}_i^k + \bar{v}_i^{k+1} \\ \bar{v}_{\min} < \bar{v}_i^k < \bar{v}_{\max} \\ \bar{x}_{\min} < \bar{x}_i^k < \bar{x}_{\max} \end{cases} \quad (18)$$

When the target function threshold is reached or the maximum iteration algebra is reached, the loop is jumped out and the fitness value is judged.

In this paper, the energy saving rate and the operating cost saving rate are respectively selected as the fitness function. When the fitness function is less than 0, set the start/stop variable to 0, the cold-hot power supply system does not start, and calculate the corresponding relevant parameters according to the distribution system. When the fitness function is greater than 0, the start-stop variable is set to 1, and the optimization algorithm results are output.

The constrained problem of particle swarm optimization is mainly to deal with equality and inequality constraints by limiting the search range of particle swarms into feasible solutions and by constructing penalty functions. For equality constraints $h_i(x)=0(i=1,2,3..., m)$, penalty function is

$$\alpha_1(x) = \sum_{i=1}^m h_i^2(x) \quad (19)$$

For equality constraints $g_j(x) \geq 0(j=1,2,3..., n)$, penalty function is

$$\alpha_2(x) = \sum_{j=1}^n \frac{1}{g_j(x)} \quad (20)$$

5 Results and discussions

5.1 Analysis of controllable parameter changes under different operating modes

In the summer load condition, the fuel consumption and the proportion of extraction steam of the trigeneration system under following the electric load, following the thermal load, optimal PES, and optimal OCS operation modes are shown in Figure 2.

The proportion of extraction steam in different operating modes in summer is mainly affected by the external cooling load. When the cooling load is large during the day, the system prefers to meet the external electrical load demand in following the electric load mode. The proportion of extraction steam will only rise when electric load decreases in the noon and the cooling load decreases in the evening; In following the thermal load mode, the proportion of extraction steam is in the maximum opening state during the day, maintaining the maximum extraction. In optimal PES mode, the change of proportion of extraction steam is corresponding towards the change of the following the thermal load mode. In the optimal OCS mode, the system reduces the proportion of extraction steam to meet the external electrical load demand as much as possible at a peak electricity price in the morning.

During the daytime, the consumption of fuel in the two gas turbines under various operation modes is basically maintained at the highest level. In the following the thermal load mode, the fuel consumption of the system rises again at 20:00, mainly due to the sudden change of external cooling load demand, resulting in a sudden increase in the thermoelectric ratio. The system prefers to satisfy the heat load, maintained maximum fuel consumption.

5.2 Comparative analysis of indicators under different operating modes

Figure 3. (a) shows the changes of PES in different modes. From the figure, it can be seen that the maximum primary energy saving rate in summer is reached at 17:00, which is 0.3847. At 12 o'clock noon, the PES reaches the peak value expect following the thermal load mode, which was mainly caused by the increase of the equivalent load-to-electricity ratio at this time. Except for the time when the two thermoelectric ratios suddenly increase at 12:00 and 8:00~20:00, the PES of the trigeneration system is the lowest under the following the electric load mode. The reason is that the system reduces the proportion of extraction steam, leading to a reduction in the cascade utilization of the energy, and resulting in a decrease in the PES. During the period from 9:00 to 11:00 and from 13:00 to 17:00, the results of optimal PES mode coincide with the following the thermal load mode, indicating that using the following the thermal load mode can achieve the best PES during the summer period.

Figure 3. (b) shows the change in the OCS for different operating modes under typical daily load conditions in summer. It can be seen from the figure that the maximum OCS at the typical summer day can reach 0.4730. The OCS increases first and then decreases, and then increases, and the trend is mainly due to peak and normal electricity price. The largest OCS in summer also occurs in the morning, and reaches a peak again at 18:00 and 19:00, mainly due to the peak electricity price at this time and the external large load demand. From 23:00 to 7:00 the next day, the OCS of the other three operating modes is less than 0 in this time.

6 Conclusions

This paper proposed two operation modes of trigeneration system, which are optimal primary energy saving (PES) mode and optimal operating cost saving mode, and get the optimal operation results with PSO in the load situation of a typical summer day.

The optimal PES operation mode and the optimal OCS mode of proposed in this paper have better indicators than the traditional operation mode. According to the balance of supply and demand, the optimal PES operation mode and the optimal OCS mode waste less energy than the traditional operation mode. In conclusion the optimal operation modes proposed in this paper have a certain realization value from the perspective of indicators and feasibility.

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