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OPTIMAL OPERATION FOR COMBINED COOLING HEATING AND POWER MICROGRID CONSIDERING NONLINEAR MODELING AND LOAD SHIFTING

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ABSTRACT

In view of the volatility of renewable energy and the randomness of load in the CCHP micro-grid, and considering that the shiftable loads model is an important means of demand side response, this paper studies the operation optimization of the system from the perspective of nonlinear modeling and load shifting. Firstly, the nonlinear model of the main equipment is established based on the nonlinear interpolation method. Then, the Shiftable loads model and the system optimization operation model with the objective functions of primary energy consumption (PEC), carbon dioxide emission (CDE) and daily operation cost (COST) are constructed. CPLEX is used to solve the above models. Finally, the effects of the nonlinear model and the linear model on the optimal operation of the system under the three objective functions before and after the load shifting are analyzed by numerical simulation. The results show that the nonlinear model can better respond to the load curve after translation than the linear model, so that the impact of load shifting on the optimal operation of the system is more obvious.

Keywords: CCHP micro-grid, Shiftable loads, Nonlinear model, Optimal operation, Multi-objective.

NONMENCLATURE

Abbreviations	
AC	Absorption chiller
COP	coefficient of performance
CDE	carbon dioxide emission
COST	daily operation cost
EC	electric chiller
GB	gas boiler
GT	gas turbine
HE	heat exchanger
HRSG	heat recovery steam generator
HST	heating storage tank
LP	linear programming
MILP	mixed integer linear programming
PEC	primary energy consumption
PV	photovoltaic cell
P	electric power
Q	thermal power
TOU	time of use electric price
CCHP	Combined Cooling Heating and Power
Symbols	
CDE	the CO2 emission conversion factor
C	the daily total cost
F	The fuel consumption
k	the site-to-primary energy conversion factor
K	the operation and maintenance cost of facility
PLR	the partial load factor
ε	the binary variable

1. INTRODUCTION

In order to meet the increasing energy demand and alleviate the pressure of environmental pollution control, due to the Combined Cooling Heating and Power (CCHP) micro-grid has the characteristics of high energy efficiency and low greenhouse gas emissions [1], cause its energy management and operation optimization has become a significant research topic [2].

The model selection of the main facility plays an important role in the selection of the system operation strategy in the operation optimization of CCHP micro-grid. In the nonlinear model, the facility of system often working under part load operation, and the operating efficiency of the facility is often lower than the rated operating efficiency, which makes it cost more than the linear model. Meanwhile, the operational optimization objective function of CCHP microgrid also has an important impact on the choice of operational strategy.

With the continuous deepening of the power market reform and development of the smart meter system, the optimized operation direction of the existing CCHP micro-grid gradually shifts from the supply side to the demand side. At present, more and more researches focus on the impact analysis of the optimized operation shiftable loads model based on the time-of-use electricity price [3-5]. Ref. [4,6,7] reveal that the shiftable loads model can effectively reduce the operating cost of the CCHP micro-grid.

The existing study rarely mentions the selection of the facility simulation models for the operational optimization of CCHP micro-grid with shiftable loads model, nor for the detailed analysis of shiftable loads model with different objective functions in the energetic, environmental and economic aspects, respectively.

This paper aim to comparative analyze the optimization results of nonlinear model and linear model with different objective functions for CCHP micro-grid with shiftable loads model, so as to deeply study the impact of the simulation models on the optimization strategies selection of the shifatble loads model, and optimize the selection of actual operation. Then, the potential of the shiftable loads model to improve the energy conservation, environmental protection and economy of the CCHP micro-grid is studied.

2. CCHP MICRO-GRID MODEL

2.1 System structure

The CCHP micro-grid model consist of gas turbine (GT), gas boiler (GB), heat recovery steam generator (HRSG), photovoltaic cell (PV), absorption chiller (AC), electric chiller (EC), heat exchanger (HE), heating storage tank (HST), battery and other facility. The system structure and energy flows of the CCHP micro-grid are shown in Fig. 1.

The mathematical model of the main facility can refer to ref. [6,8-12].

2.2 Linearization method

The existing literature usually uses the intelligent algorithm to solve the problem of MINLP (Mixed-Integer Nonlinear Programming), it takes a long time and a lot of computing resources, however, only obtains the relative optimal solution. To this end, the nonlinear model in the actual operating conditions needs to be transformed into a linear model to facilitate model solving and online application. Yet the simplified linear model is often too simple to reflect the system operation status. In view of the above problems, this paper combines piecewise linearization with binary to convert the nonlinear relationship between the output of the main facility and other physical quantities into a linear relationship.

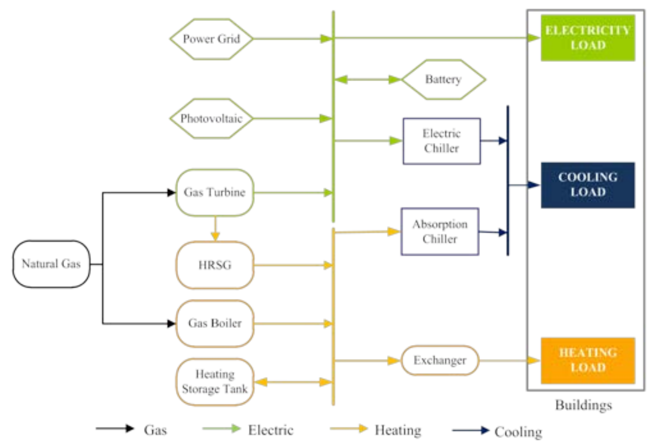


Fig 1 The system structure and energy flows of the CCHP

In this paper, the nonlinear method of gas turbine, HRSG, gas boiler, electric chiller and absorption chiller is linearized by the above method, which converts the original MINLP problem into MILP (mixed integer linearity Programming) problems to facilitate system optimization based on Ref. [3, 13].

2.3 Shiftable loads model

Through shifting the shiftable loads on the demand side to optimize the supply-demand matching is an important means of demand side response management. The shiftable loads in the CCHP micro-grid includes electric load, cooling/heating load and domestic hot water load. The shifatble loads can be flexibly shifted at different time periods under the requirements of system operation or users' will, the total load in the entire scheduling period is constant before and after the load shifting. In this paper, based on the time-of-use electricity price mechanism, the electric load and cool/heating load and domestic hot water load in the CCHP micro-grid are shifted, so as to improve the matching degree between the demand side and the supply side of the system, furthermore improve the integration energy efficiency and operational economy of system from the supply side. Detailed shiftable loads model is described in Ref. [14-16].

3. OPTIMIZE OPERATION

3.1 Objective function

3.1.1 PEC

PEC refers to convert the amount of fuel consumed by the system and the purchased electricity into the same primary energy, and can be defined as eq. (1).

$$\mathrm{PEC} = \left(F_{f,GT} + F_{f,GT}\right) \cdot \mathrm{k}_f + \frac{\mathrm{P}_{\mathrm{grid}}^{buy}}{\eta_e \eta_d} \cdot\cdot \mathrm{k}_e \tag{1}$$

Where, $m_{f,GT}$ and $m_{f,GT}$ are the total fuel consumption of gas turbine and gas boiler, respectively (kWh); $\mathrm{P}_{\mathrm{grid}}^{buy}$ is the purchasing electricity from the main grid (kWh); η_e and η_d are the grid generation efficiency and grid transmission efficiency, respectively; k_f and k_e are the site-to-primary energy conversion factor of the fuel and electricity, respectively.

3.1.2 CDE

Carbon oxide emissions are used as environmental criteria, can be defined as eq. (2).

$$\min CDE = \frac{\mathrm{P}_{\mathrm{grid}}^{buy}}{\eta_e \eta_d} \cdot cde_{grid} + \left(F_{f,GT} + F_{f,GT}\right) \cdot cde_{fuel} \tag{2}$$

Where, cde_{grid} and cde_{fuel} are the CO2 emission conversion factor of the fuel and electricity, respectively.

3.1.3 COST

The operation cost is defined as eq. (3)-(6).

$$\min C = C_{fuel} + C_{om} + C_{grid} \tag{3}$$

$$C_{fuel} = \sum_{t=1}^{T} \left(m_{f,GT}(t) + m_{f,GB}(t)\right) \cdot f_{ng} \tag{4}$$

$$C_{om} = \sum_{i=1}^{N} \sum_{t=1}^{T} K_{om,i}(t) P_i(t) \tag{5}$$

$$C_{grid} = C_{ph}(\mathrm{t}) \cdot \mathrm{P}_{grid}^{buy}(t) \tag{6}$$

Where, C is the daily total cost (¥); C_{fuel} is the fuel purchasing cost (¥); C_{om} is the operation and maintenance cost (¥); C_{grid} is the electricity purchasing cost (¥); $m_{f,GT}$ and $m_{f,GB}$ are the gas fuel consumption of gas turbine and gas boiler, respectively (m3/h); f_{ng} is the natural gas price (¥/m3); N symbols the total number of facility; $K_{om,i}$ symbols the operation and maintenance cost of facility electricity price(¥/kWh); $\mathrm{P}_{\mathrm{grid}}^{buy}$ is the purchasing electricity from the main grid (kWh). (¥/kWh), P_i symbols the outputs of facility (kWh); C_{ph} is the time-of-use

3.2 Constraints

(1) Energy balance

Eq. (7)-(9) includes electric balance, heating balance and cooling balance, respectively.

$$P_{f,GT}(\mathrm{t}) + \mathrm{P}_{PV}(\mathrm{t}) + \mathrm{P}_{BAT,C}(t)(t) - \mathrm{P}_{BAT,C}(t)(t) + \mathrm{P}_{\mathrm{grid}}^{buy}(t) = P_{EL}(t) + Q_{f,EC}(t)/COP_{EC,PL} \tag{7}$$

$$Q_{f,HRSG}(t) + Q_{f,GB}(t) + Q_{disch}(t) - Q_{ch}(t) = \mathrm{Q}_{HL}(t)/\eta_{HE}(t) + Q_{f,AC}(t)/COP_{AC,PL} \tag{8}$$

$$Q_{f,AC}(t) + Q_{f,EC}(t) = \mathrm{Q}_{CL}(t) \tag{9}$$

Where, $P_{EL}(\mathrm{t})$, $\mathrm{Q}_{HE}(\mathrm{t})$ and $\mathrm{Q}_{CL}(\mathrm{t})$ are the demand side loads of electric power, heating power and cooling power, respectively (kWh).

(2) Electric power limits of the main grid

In order to ensure the safety of the micro-grid and the main grid, there is an upper limit on the amount of electricity purchased from the main grid. And the context suppose that the micro-grid doesn't sell electricity to the main grid.

$$0 \le \mathrm{P}_{grid}^{buy}(t) \le \varepsilon_{grid}^{buy}(\mathrm{t}) \mathrm{P}_{\mathrm{grid}}^{buy,max} \tag{10}$$

Where, $\mathrm{P}_{\mathrm{grid}}^{buy,max}$ is the upper limited value of purchasing electric power from the main grid; $\varepsilon_{\mathrm{grid}}^{buy}$ is a binary variable that determine the state of the CCHP micro-grid purchasing electric power from the main grid.

(3) Power limits of facility

During the system operation, each facility should operate between the lower and upper limits of the generation.

$$\begin{cases} \varepsilon_x(\mathrm{t}) \mathrm{P}_x^{min} \le \mathrm{P}_x(t) \le \varepsilon_x(\mathrm{t}) \mathrm{P}_x^{max} \\ \varepsilon_x(\mathrm{t}) \mathrm{Q}_x^{min} \le \mathrm{Q}_x(t) \le \varepsilon_x(\mathrm{t}) \mathrm{Q}_x^{max} \\ \varepsilon_x(\mathrm{t}) \epsilon \{0,1\} \end{cases} \tag{11}$$

Where, P_x and Q_x symbol the outputs power for

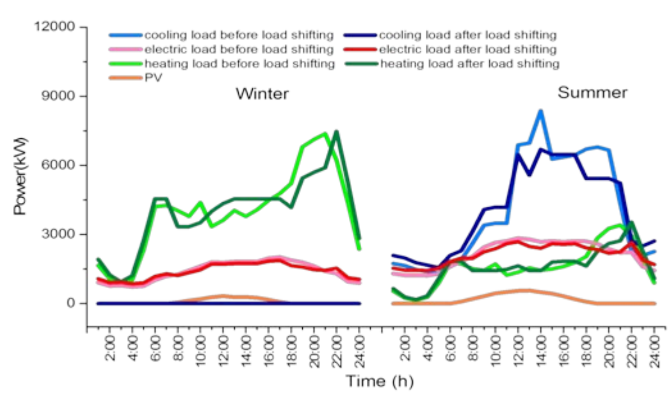


Fig.2 Cooling, heating and electric loads before and after loads shifting and PV output power

all types of power generation equipment and thermal generation equipment, respectively. P_x^{min} and Q_x^{min} is the lower limited value of all types of power generation equipment and thermal generation equipment, respectively. P_x^{max} and Q_x^{min} is the lower limited value of all types of power generation equipment and thermal generation equipment, respectively. The output power constraints of battery and heating storage tank refers to Ref. [5].

4. RESULTS AND DISCUSSIONS

The hotel building in Shanghai is selected as the base case study, and the winter load, excessive load and summer load of typical day is shown in Fig.2. In the example, the system operation mode is set to be grid-connected to the network but don't sell electric power to the main grid. The TOU electricity price and natural gas price references the ref. [17,18].

Two models are established according to the linearization of the main facility output power in the system.

Model I: The output power of the main facility of the system are the linear model.

Model II: The output power of the main facility of the system is a nonlinear model. During the operation.

4.1 Analysis of Optimized Scheduling Results of Model I and Model II after shifting based on COST

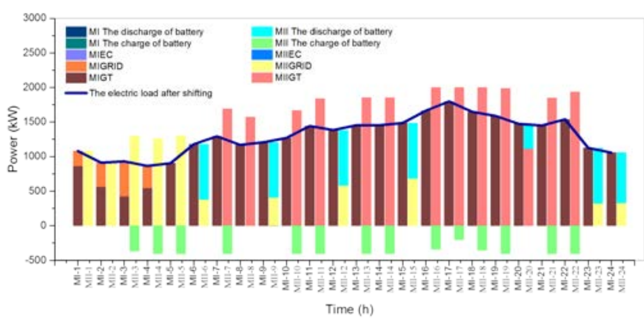
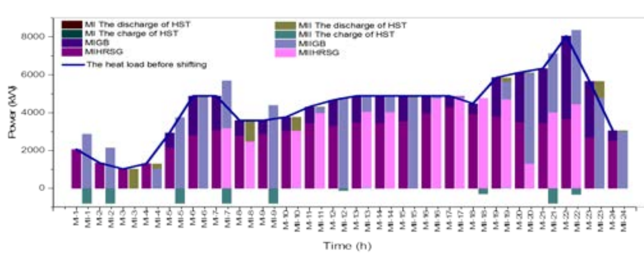


Fig.3 Comparative analysis of output powers of electric balance equipment of model I and model II after load shifting in winter



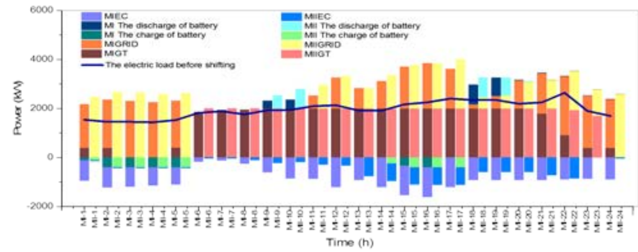


Fig.5 Comparative analysis of output powers of electric balance equipment of model I and model II after load shifting in summer

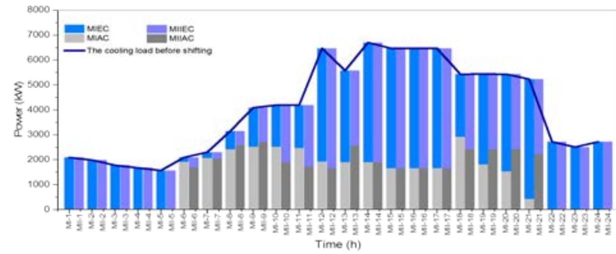


Fig 6 Comparative analysis of output powers of cooling balance equipment of model I and model II after load shifting in summer

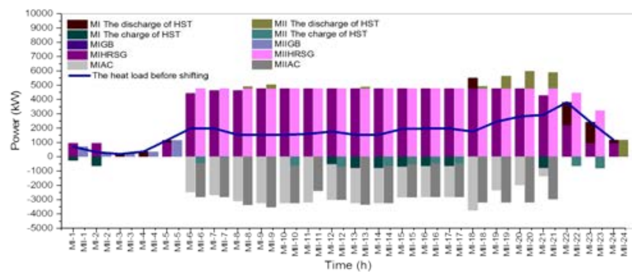


Fig.7 Comparative analysis of output powers of heating

As shown in Fig 3-7, the optimized operation results demonstrate that after the loads shifting in different seasons based on COST criteria: compared with the model I, the gas turbine output electric power period of the model II is mainly concentrated in the non- valley period. Meanwhile, the total output electric power of the gas turbine, the output heating power of HRSG and the output cooling power of electric chiller is reduced, however, the total output heating power of the gas boiler is increased, the electric power charge and discharge times of the battery and the heating power storage and release of the heating storage tank is increased. The reason is that under the conditions of the demand side and the PV output electric power is known, the operating conditions of the main facility such as the gas turbine, HRSG and the electric chiller of Model II are all in the variable working state, when the gas turbine is in the period of low load demand period, such as valley period, the operating efficiency of the gas turbine is low, and vice versa. Therefore, in the model II, for the valley period, the system preferentially purchases electricity from the main grid to meet the power demand on the load side, at the same time, the priority of the gas boiler to meet the heating load demand. While during the flat and peak periods, the system will try to make the gas turbine run at rated power. Under the load condition where the cooling load demand is not 0 kW, the excess gas turbine heating supply is preferentially used for the cooling demand of the absorption chiller, thereby reducing the degree of dependence of the system on the electric chiller. From the perspective of heating-electric ratio, the average thermoelectricity on the load side after translation is higher than the average thermoelectric ratio of the gas turbine. The average heating-electric ratio of the gas turbine of Model I is higher than that of Model II. In order to achieve energy balance between the energy supply side and demand side, the system increases the degree of dependence on the battery and the heating storage tank.

4.2 Results analysis of Model I and Model II in different objective functions

For the horizontal analysis of Tables 1-2, in Model I and Model II, the PEC, CDE, and COST in the summer after load shifting are reduced, while in winter, there has slightly increase. There may be two reasons for this, firstly is that the main equipment such as the gas turbine in winter is almost in partial load operation, and the average operating efficiency of the system is obviously below other seasons; secondly, the difference between shiftable loads model based on time-of-use electricity price. At the same time, the optimization results indicated that the system with the PEC and CDE as the objective function, the optimization results of the shiftable loads model before and after loads shifting are more obvious than the system with COST as the objective function.

Typical day	PEC		CDE		COST	
	Feb	Jul	Feb	Jul	Feb	Jul
After shifting	220798.5	270550.3	32602.4	61548.3	39155.6	46750.7
Before shifting	218717.6	284987.9	31829.5	69916.2	38345.6 4	47996.5

Table 1 The results analysis of Model I in the different objective functions

Typical day	PEC		CDE		COST	
	Feb	Jul	Feb	Jul	Feb	Jul
After shifting	1547 50.1	2573 13.9	306 00.2	587 52.1	3512 3.4	438 41.6
Before shifting	1512 29.8	2780 59.3	303 61.7	662 80.9	3600 3.0	452 39.6

Table 2 The results analysis of Model II in the different objective functions

The longitudinal analysis of Tables 1-2 is carried out. In the optimization system of three different objective functions, model II is superior to model I. The reason is that the main power output models in Model II are nonlinear models, which can better respond to the load curve after loads shifting, and concentrate the gas turbine output period in the flat period and peak period to improve the operating efficiency of gas turbine and other equipment, simultaneously increase the amount of purchasing electricity from the main grid.

5. CONCLUSIONS

In this paper, the nonlinear model of the main equipment is established based on the nonlinear interpolation method. The influence of the linear model and the nonlinear model on the optimal operation results of the shiftable loads model based on time-of-use electricity price is studied. Then in the nonlinear model and the linear model, the influence of the shiftable loads model based on time-of-use electricity price on the optimal operation results of the PEC, CDE and COST as the objective function system is analyzed. The results show that:

(1) Compared with the linear model of the main equipment, the nonlinear model concentrates the output power period of the gas turbine in the flat period and the peak period, and increases the amount of electricity purchased from the main grid during the valley period, at the same time, increases the dependence of the system on the energy storage equipment. The results show that the selection of

different equipment simulation models, the system performance optimization strategy of the system operation is quite different.

(2) The operating cost of the nonlinear model is lower than that of the linear model, it is closer to the actual operating conditions of the system, and can better respond to the load curve after load translation. Using a nonlinear model helps to select better operation strategy in the actual process.

(3) For the shiftable loads model based on time-of-use electricity price, the system with the PEC and CDE as the objective function, the optimization results variation before and after loads shifting is more obvious than the system with the COST as the objective function. It shows that the flexible interaction between the supply-demand side has great potential in improving the energy efficiency and environmental benefits of the CCHP micro-grid system.

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