Optimization of a Combined Heat and Power Generation System with Ice Thermal Storage

Cheng-gang Cui, Xiao-fei Yang, Feng Tian, Ting-yu Gao and Zhi-cong Zhu

Abstract This paper explores the optimization of a combined heat and power generation system (CCHP) with ice thermal storage air-conditioning system in consideration of minimal cost. A CCHP requires the simultaneity of the electrical and thermal demands. However, the thermal demand is strongly time-varying or even discontinuous. The ice thermal storage provides an attractive solution to the CCHP by shifting the electrical power while more profitably exploiting the thermal energy. The optimization of the simultaneous use of a gas turbine, an absorption chiller, a brine chiller, and an ice-storage tank to satisfy given electricity, heat, and cooling demands is considered. An MINLP algorithm is used to develop optimal operating strategies for the cogeneration system. Case study is based on a building belonging to Shanghai Advanced Research Institute. Finally, the results of economic analysis providing some guidelines of operation strategies to a CCHP with ice thermal storage.

Keywords Combined heat and power generation system · Ice thermal storage · Optimization · Case study

1 Introduction

Combined heat and power generation system (CCHP) is widely acknowledged as a key alternative for thermal and electric energy generation with respect to the separate production (SP) of cooling, heat, and electricity. It consists of the simultaneous production of electricity and heat and yields a high energy-saving effect, especially if compared to the traditional energy supply configuration. This leads to lower fuel consumption generated at a lower cost and in a more environmentally friendly way

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(Wu and Wang 2006). Due to the interaction between hot and cold electric system load, which may lead generation system can only bear part of the load electrical load and thermal load coincide. This makes the system to heat, and power load matching problem has become an important research topic (Gu et al. 2014).

Energy storage technologies have become an increasingly popular technology (Basecq et al. 2013). They can make the energy been stored during off-peak times and dispatched during peak times. In order for energy storage to make a significant impact, inexpensive storage technologies, thermal energy storage (TES), the storage of heat or cooling has been incorporated into the CCHP systems (Barbieri et al. 2012). TES can dramatically reduce payback periods in addition to improve the project's return on investment since it stores energy by using relatively simple and inexpensive technologies. However, CCHP systems that require storage exhibit transient behavior and the storage processes themselves are transient (Raine et al. 2014). Therefore, it is critical to develop effective operating strategies for CCHP systems with TES technologies (Ameri et al. 2005).

This work considers how a CCHP system with ice thermal storage can be operated in order to provide economic benefits. A MINLP model for tackling the short-term operation problem which aims at minimizing the operating cost of a CCHP system with ice thermal storage. The proposed model can take into account the situation that cooling is provided by directly using the chiller or by discharging the ice bank when electricity prices are high. The model has been tested on a CCHP system test case in south China. The computational results are discussed in terms of the quality of the solutions and the influence of ice thermal storage.

2 System Description

The CCHP system with ice thermal storage consists of a power generation unit (PGU), a waste recovery system, a cooling system, and an ice-storage air condition system as shown in Fig. 1 (Wang et al. 2010). In this paper, a cooling storage system of ice-storage air-conditioning system is selected, which is composed of double-duty chiller units and ice-storage tank (Al-Abidi et al. 2012). The system load consists of cooling and electrical load. The solid and dash lines represent the cooling load flows and the electric power, respectively. PGU which consumes natural gas produces electricity and heat simultaneously to meet electrical and heat load demand. If there is excess energy, it will be stored in ice-storage air-conditioning system. If the thermal load is larger than that of the amount PGU provides, the ice-storage air-conditioning system provides additional energy to the system.

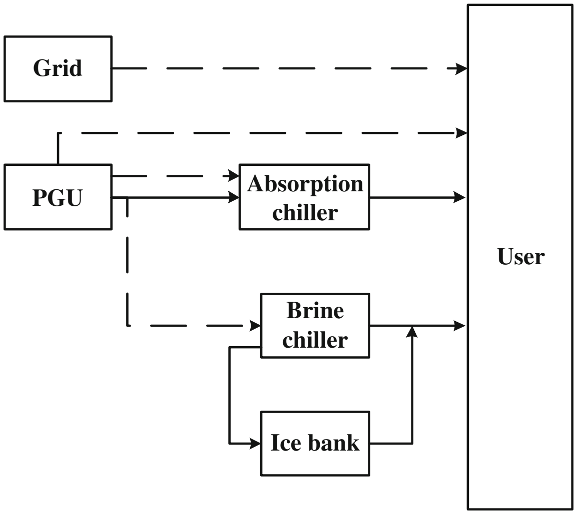

Fig. 1 Energy flow diagram of CCHP system

3 Model Formulation

3.1 Problem Description

The aim of this paper was to develop a method to generate the optimal operation of a CCHP system installed with ice-storage system in which the electric grid and a local thermal network have been considered. The total net present cost is selected as the evaluating criteria, which is used as the optimal objective to be minimized. An ice TES unit is used to avoid the discontinuous operation of the CCHP system and to increase the number of operating hours.

The optimal operations of CCHP problem we want to tackle can be stated as follows:

- Generation units with fixed size, performance curves, and start-up/warm-up times;
- Ice-storage tank with fixed capacity and constant loss rate;
- Time-dependent price of electricity;
- Determine the following for each time period of a time T horizon $[t_0, t_f]$:
  - The set of units to be switched on
  - The value of the operative variables of each unit
  - The storage tank level

which minimize the operating cost while satisfying the demands of thermal and electric.

3.2 Model Description

A mixed integer nonlinear programming (MINLP) model concerning the aforementioned scenario problems has been developed. The mathematical model is reported in the following by a set of constraints and an objective.

1. Set the energy optimization scheduling period as $[t_0, t_f]$, the energy scheduling interval is T, the scheduling period includes N_t time intervals T, and $t_i = [t_0 + (i - 1)T, t_0 + iT]$, where $i = 1, \ldots, N_t$.
2. Set energy type as $j = 1, \ldots, N_j$, where N_j is the total number of energy types. For example, set energy type $j = 1$ for power, energy type $j = 2$ for heating, and energy type $j = 3$ for cooling in CCHP system.
3. Set device number as $k = 1, \ldots, N_k$. Set N_k represents all the devices, including N_s represents the number of types of energy conversion devices, N_c represents the number of complementary multi-energy devices, N_m represents the number dynamic energy devices, and N_n represents the number of the energy storage devices.
4. Set U as the devices, and Q as the energy generating or using by the devices. For a device, it can be expressed as U_k. The generating or using energy can be represented as $Q_{k,j}$. For example, the internal combustion engine can be expressed as U_1; when generating electric power, it is represented as $Q_{1,1}$, when generating heat, it is represented as $Q_{1,2}$; and when generating cooling, it is represented as $Q_{1,3}$.

3.2.1 Parameters and Variables

1. Time-varying parameter
   Time-varying parameters are the parameters that may change over time periods as demand fluctuations or the ambient temperature. Therefore, they have different values for each time period t:
   - $p_j(i)$: the energy demands at time t;
   - $\mathrm{pb}_j(i)$: the energy purchase price at time t;
   - $\mathrm{ps}_j(i)$: the energy sale price at time t;
2. Constant
   - $\mathrm{cm}_{k,j}$: device maintenance costs, which is proportional to the amount of energy produced;
   - cs_k: start-up costs, which is proportional to the number of starts;
   - $\mathrm{ch}_{k,j}$: the loss of energy storage devices, which is proportional to the length of time;

3. Continuously variable
   - $Q_{k,j}(i)$: the energy j supply or consumption of device k at time I;
   - $\Delta Q_{k,j}(i)$ represents the amount of energy j stored in the energy storage device variation between time i and $i-1$;
   - $S_{k,j}(i)$: the energy j stored in energy storage devices k at time i;
4. Binary variable
   - $z_k(i)$: the state variables of device k at time i;
   - $m_j(i)$: state variables represent whether energy j is purchased;

3.2.2 Objective

The objective is shown as follows:

$$\min \sum_{i=1}^{N_t} C_b(i) - \sum_{i=1}^{N_t} C_s(i) + \sum_{i=1}^{N_t} C_{\text{on}}(i) + \sum_{i=1}^{N_t} C_l(i).$$

$C_b(i)$ is the energy cost of all the devices during time i. It is given by the sum of the amount of fuel each device is utilizing multiplied by its specific cost.

$$C_s(i) = \sum_{j=1}^{N_j} \sum_{k=1}^{N_k} p_s(i) Q_{k,j}(i)$$

$C_{\text{on}}(i)$ is the start-up cost of all the devices during time i. It is given by the extra cost associated to the start-up procedure.

$$C_{\text{on}}(i) = \sum_{k=1}^{N_k} \text{cs}_k(i) Z_k(i)$$

$C_s(i)$ is calculated by multiplying the amount of electric energy hourly purchased or sold to the grid.

$$C_s(i) = \sum_{j=1}^{N_j} \sum_{k=1}^{N_k} p_s(i) Q_{k,j}(i)$$

3.2.3 Constraints

1. **Energy load balance constraint**
   The balance constraint ensures that customer requirements of energy are always fulfilled by devices generating this energy j during time i as follows:

$$\sum_{k=1}^{N_s} Q_{j,k}(i) + \sum_{k=1}^{N_c} Q_{j,k}(i) + \sum_{k=1}^{N_m} Q_{j,k}(i) + \sum_{k=1}^{N_n} \Delta Q_{j,k}(i) = P_j(i),$$

   where $Q_{k,j}(i)$ is the energy j generated or consumed by device k and $\Delta Q_{j,k}(i)$ is the variation of energy j stored in device k during time i.
   To make it easy to satisfy the constraints, a slack variable sl_j is introduced to solve the constraints.

$$\sum_{k=1}^{N_s} Q_{j,k}(i) + \sum_{k=1}^{N_c} Q_{j,k}(i) + \sum_{k=1}^{N_m} Q_{j,k}(i) + \sum_{k=1}^{N_n} \Delta Q_{j,k}(i) + \mathrm{sl}_j = P_j(i)$$

2. **Device start-up constraint**
   The "start-up" constraints are used in order to set a maximum number of start-up procedures that can be tolerated by each device in order to avoid damages.

$$\sum_{i=1}^{N_T} \Delta T_{k,i} \leq N_k$$

   To ensure that the variable has value 1 at time i if, and only if, device k was off at time i, we introduce the following constraints

$$\begin{aligned} &\Delta T_{k,i} \geq Z_k(i) - Z_k(i-1) \\ &\Delta T_{k,i} \leq 1 - Z_k(i-1) \\ &\Delta T_{k,i} \leq Z_k(i) \end{aligned}$$

3. **Performance constraint**
   The performance constraint ensures the performance of the device. For each device, the input variables (consumed fuel and electricity) are related to the output variables (generated heat, electricity, cooling) by a performance function.

   (a) Gas turbine
   As the prime mover, the performance of gas turbine will directly affect the performance of CCHP systems. The main factors that affect the performance of the gas turbine are temperature, absolute humidity, altitude, air inlet pressure loss, and exhaust port back part load rate. For the sake of simplicity of the model, the gas turbine power output, fuel consumption,

and the corresponding heat exhaust of recyclable are considered in this paper. The model coefficients are fitted by gas turbine operating data.
Fuel consumption constraints:

$$Q_{k,0}(i) = \sum_{j=1}^{m} a_n^j Q_{k,j}^n(i) + \cdots + a_2^j Q_{k,j}^2 + a_1^j Q_{k,j}(i) + b_j.$$

Heat recycling constraints:

$$Q_{k,j'}(i) = c_n^j Q_{k,j}^n(i) + \cdots + c_2^j Q_{k,j}^2(i) + c_1^j Q_{k,j}(i) + b_j.$$

(b) Chiller
In the CCHP system, chiller system is operated at part load at most time. Different device load will case a different performance coefficient. The dual-mode chillers are modeled by the electricity consumed, where the model is divided into a cooling condition and an ice conditions model. The regression coefficients of each model are different from each other.

$$Q_{k,j'}(i) = a_n Q_{k,j}^n(i) + \cdots + a_2 Q_{k,j}^2(i) + a_1 Q_{k,j}(i) + b$$

(c) Ice-storage system
The ice-storage air-conditioning device is different from the conventional air-conditioning device. The ice bank is not a power device, but the performance of ice melting has a great impact on the operation of the ice-storage system. For simplicity, the maximum ice-melting efficiency is a constant in this paper.
Ice-storage constraint:

$$Q_{\min,j} \le Q_{k,j}(i) \le Q_{\max,j}$$

where $Q_{k,j}(i)$ is the ice stored in the device during time i, $Q_{\min,j}$ and $Q_{\max,j}$ are the minimum and maximum value of ice stored in the device.
Melting rate constraint:

$$Q_{k,j}(i) - Q_{k,j}(i-1) \le \Delta Q_{\max,j}$$

where $\Delta Q_{\max,k,j}$ is the max melting rate between time i and time $i-1$;
Variation constraints:

$$Q_{k,j}(i) = Q_{k,j}(i-1) + \Delta Q_{k,j}(i)$$

where $\Delta Q_{k,j}(i)$ is the variation of ice between time i and time $i-1$;
All the performance functions are fitted by a polynomial curve fitting method.

3.2.4 Solving Method

The model is written in the YALMIP algebraic modeling language (Lofberg 2004) and the resulting MINLP is solved with Bonmin optimizer.

4 Case Study

4.1 Problem Description

In order to validate the proposed mathematical model-based approach, a CCHP system with ice thermal storage located in the south of China has been taken into account. A proper dataset including both thermal and electric energy consumptions in the year 2013 was considered. The system is operated during a day by 1 h. The hourly power load demand is [300, 300, 300, 300, 320, 320, 662, 852, 852, 980, 972, 972, 972, 972, 862, 760, 665, 654, 495, 423, 300, 300, 300] and the cooling load demand is [0, 0, 0, 0, 0, 0, 262, 372, 470, 471, 472, 672, 672, 672, 462, 360, 161, 154, 95, 0, 0, 0, 0, 0] ton. The gas price is 2.4 yuan, the electricity prices are 1.287 yuan in peak period (8:00–11:00 and 18:00–21:00), 0.817 yuan in normal period (6:00–8:00, 11:00–18:00, and 21:00–22:00), and 0.305 yuan in valley period (22:00–6:00 the next day).

4.2 Device Model

In the case the cooling load is provided by adsorption chillers or ice-storage systems and electrical load is supplied by gas turbine generator or the grid, set energy $j = 1{:}3$ is electric, cooling, and gas; device $k = 1{:}4$ is the gas turbine, dual chiller in cooling, dual chiller in ice, and ice bank. All the device models are shown as follows:

1. **Gas turbine Model**
   Gas consume:

$$Q_{1,4}(i) = 0.333 * Q_{1,1}(i) + 239.2$$

   Heat recycling:

$$Q_{1,2}(i) = 2.56039 * Q_{1,1}(i) + 1{,}546.024$$

2. **Duplex-mode chillers**
   Cooling mode:

$$\begin{aligned} Q_{2,3}(i) = {} & \left(10\left(Q_{2,1}(i)\right)^3 - 280\left(Q_{2,1}(i)\right)^2 + 23.64 Q_{2,1}(i) \right. \\ & \left. + 0.8392\right)/1.15 \; Q_{2,3}(i) \leq 100 \end{aligned}$$

Ice mode:

$$Q_{3,3}(i) = 0.565 * (10 * (Q_{3,1}(i))^3 - 280 * (Q_{3,1}(i))^2 + 23.64 Q_{3,1}(i) + 0.8392) \; Q_{3,3}(i) \leq 100$$

3. **Ice bank**
   Maximum ice-storage constraint:

$$Q_{4,3}(i) \leq 500$$

Ice-storage constraint:

$$Q_{4,3}(i) = Q_{4,3}(i-1) + \Delta Q_{4,3}(i)$$

Maximum melt constraint:

$$\Delta Q_{4,3}(i) \leq 100$$

4.3 Results and Analysis

The numerical results obtained by the MINLP-based optimization tool of the case are shown in Fig. 2. The reader can notice that the operation is greatly affected by the electric price and the demand load in peak and valley price policy. The duplex system works at ice mode when there is no cooling demand during electric valley

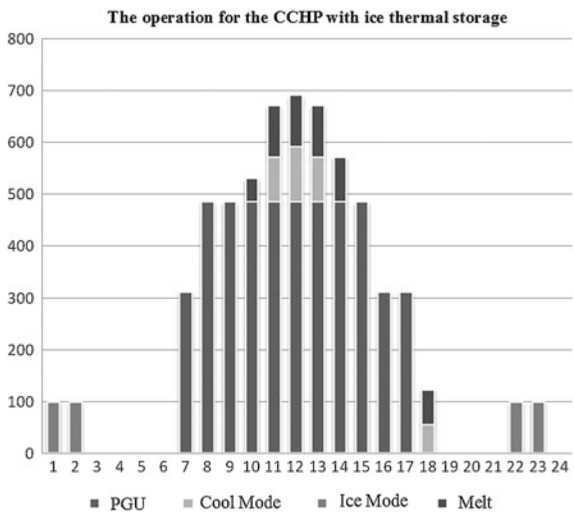

Fig. 2 The operation for the CCHP with ice thermal storage

price period. The prime mover works under the variable operating conditions if the cooling load is greater than the economic cooling load during the electricity price peak and flat period. The prime mover works under the variable operating conditions when the cooling demand is larger than the nominal load of prime mover. The ice bank system works at melt mode, and it is operating as a supplement to the prime mover where the cooling load is greater than the nominal load of prime mover and less than the sum of the nominal load of prime mover and melt load of ice thermal storage. The ice bank system works at melt mode, and the duplex chiller works at cooling mode where the cooling load is greater than the sum of the nominal load of prime mover and melt load of ice thermal storage. They are both operated as a supplement to the prime mover. They also work at the same mode when the cooling load is less than the nominal load of prime mover. From the figure, we can notice that the ice-storage system can reduce the cost of the CCHP system by a suitable operation.

5 Conclusion

To improve the economics of the energy system, an ice thermal storage system is introduced to the CCHP system. We also developed a MINLP optimization model for the systems operation. The MINLP model allows to deal with the system involving ice thermal storage. The model can handle units with nonlinear performance and solved by a MINLP optimizer. The case study shows that suggest that, under TOU conditions, the ice thermal storage system can effectively improve the economy of the CCHP system, and make the operation of the system more flexible.

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References

Al-Abidi AA, Bin Mat S, Sopian K et al (2012) Review of thermal energy storage for air conditioning systems. Renew Sustain Energy Rev 16(8):5802–5819

Ameri M, Hejazi SH, Montaser K (2005) Performance and economic of the thermal energy storage systems to enhance the peaking capacity of the gas turbines. Appl Therm Eng 25(2):241–251

Barbieri ES, Melino F, Morini M (2012) Influence of the thermal energy storage on the profitability of micro-CHP systems for residential building applications. Appl Energy 97:714–722

Basecq V, Michaux G, Inard C et al (2013) Short-term storage systems of thermal energy for buildings: a review. Adv Build Energy Res 7(1):66–119

Gu W, Wu Z, Bo R et al (2014) Modeling, planning and optimal energy management of combined cooling, heating and power microgrid: a review. Int J Electr Power Energy Syst 54:26–37

Lofberg J (2004) YALMIP: a toolbox for modeling and optimization in MATLAB. In: IEEE international symposium on computer aided control systems design. IEEE, pp 284–289

Raine RD, Sharifi VN, Swithenbank J (2014) Optimisation of combined heat and power production for buildings using heat storage. Energy Convers Manag 87:164–174

Wang JJ, Jing YY, Zhang CF (2010) Optimization of capacity and operation for CCHP system by genetic algorithm. Appl Energy 87(4):1325–1335

Wu DW, Wang RZ (2006) Combined cooling, heating and power: a review. Prog Energy Combust Sci 32(5):459–495

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