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Multi-objective optimal operation and energy coupling analysis of combined cooling and heating system

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ABSTRACT

The internal coupling relationships are essential issues that impeding the efficient operation of a complicated CCHP (combined cooling, heating and power) system. In this paper, a multi-objective optimization model is proposed, aiming to maximize the energy-saving ratio and minimize the energy costs of a micro-CCHP system consisting of an absorption and electric chiller. Based on a novel co-simulation optimization platform, the NSGA-II (Non-dominated Sorting Genetic Algorithm-II) is employed to identify a series of compromised optimal operation strategies with different operational parameters. Moreover, the characteristics analysis is further made to reveal the energy coupling between these conflicting objectives in the operation of CCHP system. The implementation of this method will be beneficial to understand the internal energy variation and improve the system performance, thus providing a guiding principle for CCHP system optimization.

1. Introduction

A CCHP (combined cooling, heating and power) system is broadly defined as a comprehensive production distributed system based on energy cascaded utilization, which can meet the energy demand by generating electricity through ICEs (internal combustion engines), turbine engines, or fuel cells, and simultaneously provides the cooling and heating load by recovering waste heat [1]. The CCHP system can improve energy efficiency and reduce air pollutant emissions dramatically, thus attracting great attention worldwide [2–6]. CCHP systems are already applied in large-scale applications, such as industry and commercial buildings. In recent years, micro-CCHP systems have been introduced into relatively small-scale places, such as hotels, offices and domestic houses, and have already become a new research hotspot [7–10].

As a multi-generation integrated energy system, the energy management and operation strategy of CCHP systems are notably complicated. Many studies have shown that load fluctuation would seriously affect the entire system's performance. Even in certain circumstances, the energy could not be saved but the cost is still higher than that of the conventional system. Therefore, it is crucial to improve the competitiveness of the CCHP system with the optimization of the energy management, evoking great attention in all circles of the society. In addition, the overall performance of the CCHP system could further be improved by integration with other renewable energy resources, such as biomass [11,12], and solar power [13,14].

Current research can be classified into two categories: (1) basic operation strategy, (2) optimal/near-optimal operation strategy. Two basic operation strategies have been developed to operate the CCHP system either FED (following electrical demand) or FTD (following thermal demand). The effectiveness analysis of the tri-generation system based on these basic operation strategies has been described in Refs. [15–17]. Wang et al. [18] compared the performance of a CCHP system under the two basic operating modes based on the PESR (primary energy savings ratio), the exergy efficiency and the CO_2 emission reduction rate, and the sensitivity of the performance to the energetic and environmental parameters was also analyzed. Fang et al. [19] formulated the operational boundary conditions of the CCHP system, depending on load variation and integrated criteria, and a different basic operation mode is adopted for the corresponding region to achieve optimal performance. Mago et al. [20] proposed a hybrid strategy and verified its effectiveness in terms of reducing energy consumption, operating costs and greenhouse gas emissions.

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The above strategies based on the FED and FTD modes achieved the overall performance optimization and could be easily applied. However, these strategies underperform the ones derived from optimization models in terms of different indices such as energy efficiency, cost recovery and carbon emissions reduction. Therefore, other studies focused on developing an optimal operation strategy by solving the single objective or multi-objective model with optimization algorithms. Cho et al. [21] established a linear programming model with the goal of maximizing the PER (primary energy ratio), minimizing the total energy costs and carbon dioxide emissions, thus obtaining the optimal operating strategy. Hu and Cho [22] presented a stochastic multi-objective optimization model considering load uncertainty. The probability constraints were added to ensure the reliability of the optimized operation strategy, while an incentive model was designed to further study the benefits of energy conservation and emissions reduction. Liu et al. [23] proposed a configuration based on hybrid chillers and optimized the electric cooling ratio. However, the winter condition was not considered. Wu et al. [24] developed a mixed-integer nonlinear programming model of a micro-CCHP system; PESR and cost saving ratio were chosen as the objectives and calculated hierarchically, while the impacts of energy price and load variation were also investigated. Facci et al. [25] applied dynamic programming to optimize the daily set-points of the PGU under different seasonal load conditions and energy prices, intending to minimize the total costs, but the other performance aspects of the CCHP system were not studied.

Energy efficiency, economic sustainability and environmental protection are the most important aspects of optimal operation strategies of CCHP systems. However, as they often mutually influence each other, how to reach a reasonable compromise is critical. To solve this type of optimization problem, some studies convert the multiple objectives into a single objective using the linear weighting method. However, different results may be achieved due to the dependence on the weighting factors [26–28]. Meanwhile, varied operating strategies need to be selected based on different focuses, but the above methods provide few alternatives for the system operator. Given this, other works attempt to obtain the optimal solution sets by the genetic algorithm and Pareto-frontier method [29–33]. Burer et al. [31] presented a multi-objective optimization of a district cogeneration system, using the Pareto-frontier method to obtain the global solution at the minimum rate of CO_2 emissions. Abdollahi et al. [32] realized the thermoenvironomic optimization of a small-scale CCHP system using a multi-objective approach, which was solved by the genetic algorithm to find the optimal Pareto sets. Nevertheless, the coupling relationships of the CCHP system, especially the impacts of operational parameters on the objectives, remain unclear.

This paper designed a micro-CCHP system driven by a biogas-fuelled ICE and combined with electric and absorption chillers. The multi-objective optimization model maximizing PESR and minimizing energy costs is proposed considering the off-design characteristics of the facilities. Moreover, a co-simulation platform with TRNSYS (Transient System Simulation Program) and Matlab is developed, thus the NSGA-II (Non-dominated Sorting Genetic Algorithm-II) can be introduced to offer a series of compromised optimal strategies with different minimum load coefficients of the PGU and the electric cooling ratios. The system performance is further analyzed to reveal the energy coupling relationships between these objectives. The typical daily load curves of a farmland building are chosen as the study case to verify the feasibility of the presented methodology.

This paper is organized as follows: Section 2 shows the development of the micro-CCHP system model and explains its energy flows. Section 3 describes the optimization problem and, in particular, illustrates the off-design performance of the facilities. Section 4 introduces NSGA-II and proposes the co-simulation platform of TRNSYS and Matlab to implement the optimization process. Section 5 analyzes the performance under the optimal operation strategies with different operational parameters. The conclusions are summarized in the last section.

2. Micro-CCHP configuration and analysis

2.1. System design

The ICE, with good operational reliability and low initial investment, has been the widely used prime mover in small-scale CCHP systems. Given this, a micro-CCHP system with an ICE as its core is built with a hybrid cooling mode, which adopts the electric chiller with a higher COP (coefficient of performance) to increase cooling efficiency [34]. Additionally, biogas is chosen as the primary energy to further enhance the effectiveness in energy saving and emission reduction [35].

The system structure is shown in Fig. 1.

As shown in Fig. 1, the PGU, driven by biogas, generates electricity for users, the electric chiller and other equipment. When redundant power is generated, it will be fed back into the PG (power grid). Shortfall power can also be supplemented by the PG.

In addition, the waste heat produced by the PGU, including the jacket water heat and the exhaust heat, is recovered through the water-cycle subsystem. The seasonal valve is set to indicate whether the provided hot water is used for heat or to drive the absorption chiller. The gas boiler is also equipped for auxiliary. Herein the redundant heat is assumed to be fully discharged.

2.2. Energy flow analysis

The energy flow of this CCHP system should first be analyzed to study the optimal operating strategy. In Fig. 1, E_{pgu} is the electricity generated by PGU; E_{grid} represents the purchased electricity from the grid; E_{ec} is the input power of the electric chiller; and E_{pa} is the parasitic power of other electric equipment such as cooling towers and pumps; E represents the user demand for electricity.

The electricity energy balance in the CCHP system is expressed as

$$E_{pgu}(t) + E_{grid}(t) = E(t) + E_{ec}(t) + E_{pa}(t) + E_{ex}(t) \tag{1}$$

where $E_{ex}(t)$ represents the amount of electricity energy sold back to the PG in period t ($t = 1, 2, \ldots, T$). E_{grid} can be transformed into the primary energy consumption:

$$G_e(t) = E_{grid}(t) \Big/ \eta_e \eta_d \tag{2}$$

where η_e and η_d are the electricity generation efficiency and the distribution efficiency of the PG respectively; $G_e(t)$ represents the energy consumed by power generation from the PG in period t.

In addition, the power consumption of the electric chiller is

$$E_{ec}(t) = Q_{ec}(t)/COP_{ec} \tag{3}$$

where $Q_{ec}(t)$ is the power of the electric chiller in period t; COP_{ec} is the COP of the electric chiller.

Meanwhile, the required input energy of the PGU can be estimated as

$$G_{pgu}(t) = E_{pgu}(t) \big/ \eta_{pe} \eta_{te} \tag{4}$$