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Optimal design and analysis of a new CHP-HP integrated system

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ABSTRACT

A CHP-HP integrated system coupled by combined heating and power system and heat pump has been proposed previously, but its performance varies with the design and operation strategies. This paper develops a multi-objective optimal model of the new integrated system based on the comprehensive indicators, i.e. primary energy saving ratio, CO_2 emission reduction ratio and annual expense saving ratio. The key design parameters, such as the prime mover capacity (PM), the outlet temperature from heat pump and the decision value to run the PM, are optimized by genetic algorithm. In order to verify the multi-objective optimal model, a case analysis is presented. The results show that the comprehensive performance of 26.8% is the best when the PM capacity is selected as 1136 kW, the decision value is set as 0.6 and the outlet temperature from heat pump is set as 25. Moreover, a sensitivity analysis is implemented to identify how the system performance changes regarding the variation of key design parameters. Finally, it is concluded that the multi-objective optimal model is very helpful for the optimization design and practical applications of the CHP-HP integrated system.

1. Introduction

Combined heating and power system (CHP), as a high-efficiency and environmental-friendly technology, can enhance the resource energy efficiency and reduce the air pollutants and carbon emissions greatly by providing heating and power at the same time [1]. Heat pump technology has also attracted much attention due to its environmental-friendly and energy saving characteristics [2]. However, since the building load demand always varies strongly over time, the single energy system cannot show its own advantages. Therefore, system integration will be more reliable.

In the last decade years, many researchers studied the integrated system with the coupling of CHP system and heat pump (HP). When it is used for generating heating, the integration approach can be summed up in three aspects [3]. (i) The heat from the CHP system is considered as the heat source of evaporator in the HP due to its thermal stability. Han et al. [4] proposed a novel absorption-compression hybrid refrigeration system, in which the flue gas is considered as the heat source to drive the proposed system. Sun et al. [5] conducted on an experimental study of a CHP system base on absorption cycles, the heat recovery unit (HRU) is adopt to recover the exhaust steam from turbine directly. (ii) The HP system is a supplement, and the CHP system and HP system is operated independently; Wu et al. [6] presented a mixed-integer non-linear programming model of micro CCHP system basing gas engine, heat pump and adsorption chiller, the heat pump is considered as auxiliary heat supply to meet extra heating load. Cardona et al. [7] carried out the optimization of design and operation of a hybrid CHCP/HP system in terms of three criterions (economic, energetic and environmental benefits); the heat pump provides the rest thermal and cooling when the CHCP cannot afford the enough thermal and cooling to user. (iii) The outlet fluid of the HP is reheated by the heat from the CHP to realize the high temperature requirements. Smith and Few [8] presented the exergy analysis of an experimental domestic scale CHP/HP system, the CHP system provides the electricity for HP system and the exhaust heat from CHP is utilized to reheat the outlet fluid of HP system.

However, for the integration method (i), the HP efficiency is improved by increasing the evaporation temperature, but limited compared with decreasing the condensation temperature. For the integration method (ii), the HP efficiency is not improved, but it can increase the heat output. For the integration method (iii), in this passive approach, the outlet fluid has to be reheated in order to satisfy the high-temperature, since the HP cannot achieve the required temperature, and thus. Therefore, the energy-saving potential of the integrated CHP-HP system can be further explored.

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Nomenclature

Abbreviations

CHP	combined heating and power system
PM	prime mover
HP	heat pump
COP	coefficient of performance
GA	genetic algorithm
E	electricity, kW
Q	heating, kW
f	load fraction of PM
F	fuel energy, kW
cm	heating capacity of the fluid, kW/°C
PESR	primary energy saving ratio
CE	CO_2 emission
CER	CO_2 emission reduction ratio
ATE	annual total expense
ATESR	annual total expense saving ratio
N	installed equipment
C	initial capital cost
P	capital recovery factor
I	interest rate
d	service life of the equipment
CP	comprehensive performance

Greek symbols

η	efficiency
λ	key value to open the PM
β	emission conversion factor
ω	weight factor

Subscripts

i	day
j	hour
ae	auxiliary equipment
grid	grid
hp	heat pump
t	outlet temperature of heat pump
rc	rated capacity of PM
rae	auxiliary equipment of reference system
rb	boiler of reference system
rec	recovery heat of PM
b	boiler
e	electricity efficiency
tr	transmission efficiency of grid
r	reference system
n	new integrated system

Based on the principle of reasonable optimization for temperature difference and moderate integration, one CHP-HP integrated system was put forward by the authors previously [9,10]. In the above integrating system, the outlet temperature at condenser side of HP decreases actively, and then reheated to the requirement temperature through the mid-low waste heat from the CHP. The decrease of outlet temperature at condenser side decreases the compression ratio and improves the COP of HP. The proposed system shows large superiorities compared with conventional system. Moreover, the thermodynamic of integrating system is investigated in terms of second law of thermodynamics, which contributes to reveal the essential energy saving character of system [11]. Besides that, the performance characteristic of proposed system for different load conditions is evaluated under two operation strategies. The results show that the FEL (following the electricity load) operation strategy is preferred [12].

The device capacity and system optimization operation are the key factors for an expected coupling energy system. The typical optimization algorithms are always divided into the linear programming [13,14] and non-linear programming [15,16], which are usually applied to CCHP/CHP system optimization and play a useful help in the system design and operation. The other optimization algorithms have been also explored extensively, such as particle swarm algorithm [17], simulated annealing algorithm [18], artificial neural network [19] and genetic algorithm (GA) [20,21]. Moreover, in the optimization process, the optimal results are dependent on the setting of the objective goals in some extent. Different optimization functions were adopted according to the purpose of investigators. However, most of them studied the issue based on the single objective, such as energetic objective and economical objective. As the single objective cannot evaluate the system performance comprehensively and even often conflict with each other, multi-objective optimization is recommended. Jing et al. [22] optimized for the CCHP system capacity to maximize the comprehensive performance in life cycle, including primary energy consumption and environmental indicators (CO_2 emission, SO_2 emission and $PM_{2.5}$ emission), and compared the optimization results in different operating strategies. Abdollahi [23] conducted a multi-objective optimization design for a small scale CCHP system from the view of thermoenvironomic considering the thermodynamic and environmental factors, which combines the exergy efficiency and costs. In the decision-making process, the genetic algorithm was employed to seek for the Pareto optimal solutions regarding every objective. Muccillo [24] carried out the predictive analyses of cogeneration system for a hospital facility applying a multi-objective approach to seek for the optimization plant configurations that achieves the best energetic efficiency and ensures a reasonable income. Kavvadias et al. [25] developed a multi-objective optimization model in terms of economic, energetic and environmental indicators. A case of a CCHP system applied in a 300 bed hospital was examined using a multi-objective genetic algorithm in order to verify the optimization procedure, the economical and energetic performance, as well as the effectiveness of the given approach. Seijo [26] proposed an optimization method for a complex CHP process in the North of Spain, in which the artificial neural networks and adaptive neuro-fuzzy inference system are employed to develop the predictive models of the process. The multi-objective problem was proposed so as to maximize the electrical and heat outputs, as well as to minimize fuel consumption.

Therefore, a multi-objective optimization model for the new integrated system is presented. This model takes the primary energy saving ratio, CO_2 emission reduction ratio and annual expense saving ratio into account simultaneously. The operation of the new CHP-HP integrated system is based on the given heating demands. The genetic algorithm is selected to optimize the equipment capacity and operating mode of CHP-HP integrated system. Section 2 introduces the system structures of the new integrated system and presents the mathematical optimization model. Section 3 proposes the optimization objectives and constructs the GA optimization procedure. Section 4 puts forward a numerical case to verify the validity of the optimal model.