Applied Energy 215 (2018) 227–236

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Effects of different alternative control methods for gas turbine on the off-design performance of a trigeneration system

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HIGHLIGHTS

- Two control methods for gas turbine on a trigeneration system are evaluated.
- The IAT control method for gas turbine enhanced off-design performance of the trigeneration system.
- The matching between different control methods and seasons are presented and compared.
- The analysis is performed on the trigeneration system in Beijing, China.
- The sensitivity analysis of the electric price and gas price is presented.

ARTICLE INFO

Keywords:
CCHP systems
Off-design performance
Operation strategy

ABSTRACT

Thermodynamic and economic performance of the combined cooling, heating and power system (CCHP) is mainly affected by its configuration and operation strategy. In this paper, the reducing turbine inlet temperature (TIT) and inlet air throttling (IAT) control methods for gas turbines following the electric load (FEL) are used to analyze the primary energy consumption (PEC), operational cost (COST) and carbon dioxide emission (CDE) in a case of a CCHP system that satisfies the cooling, heating and electric demands of a five-star hotel in Beijing, China. The results indicate that the CCHP system with both TIT and IAT control methods has better off-design performance than separate system except for transition seasons. Since the more production of high-temperature flue gas, the IAT control method significantly reduces the fuel consumption of the auxiliary boiler to satisfy the thermal demand of the reference building, especially in hot summer and cold winter. In January, the IAT control method can decrease fuel consumption by 7.53% compared with TIT control method. Moreover, it is found that improved energy saving performance and decreased operation cost and carbon dioxide emission of the CCHP system are presented with the IAT control method at the annual performance. Finally, the sensitivity analysis of the electric price and gas price is presented for the operation cost and shows that the gas price is the most sensitive variables for the operation cost of the CCHP system.

1. Introduction

The environmental impacts and energy shortages of fossil fuel are leading researchers to develop energy-efficient technologies. Because of the benefit of energy-step-utilization, the combined cooling, heating and power (CCHP) systems have received sustained attention that can generate electricity and recover the surplus heat contained in flue gas for the generation of cooling, heating or domestic hot-water [1,2]. CCHP systems show energy-saving characteristics, economic feasibility and environmental friendliness for many applications such as residential buildings [3,4], hotel buildings [5,6], commercial buildings [7,8].

Ideally, a CCHP system achieves high-efficiency performance, and no excess energy is produced when all energy demand is satisfied by this system under the design condition. This is the best match between demand and supply. However, the off-design condition accounts for a bulk of the operation periods with the changing energy demand. Thus, the selection of the appropriate operation strategy is an essential requirement for the operation periods of the polygeneration systems [6]. Typically, the following electric load (FEL) and following thermal load (FTL) are common operation strategies. The electric demand is satisfied by the gas turbine at any moment under FEL operation. If the recovered

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https://doi.org/10.1016/j.apenergy.2018.01.053
Received 29 October 2017; Received in revised form 17 January 2018; Accepted 22 January 2018
Available online 20 February 2018
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Nomenclature

CCHP	combined cooling, heating and power
CDE	carbon dioxide emission
COMP	compressor
COMB	combustor
COP	coefficient of performance
COST	operational cost
E	electricity
F	fuel consumption
FEL	following electrical operation strategy
FTL	following thermal operation strategy
FHL	hybrid electric-thermal operation strategy
HX	hot water exchanger
IAT	inlet air throttling
PEC	primary energy consumption
Q	heat
TIT	turbine inlet temperature
TUR	turbine

Greek letters

η	efficiency
ξ	pat load rate

Subscripts

b	boiler
c	cooling
e	electricity
g	gas turbine
grid	electricity grid
h	heat
hc	heating coil
max	maximum
min	minimum
op	operation
r	recovery heat
req	demand of users
rc	the part of recovery heat for cooling
rh	the part of recovery heat for heat
rw	the part of recovery heat for hot water
w	hot water

waste heat cannot handle the heating demand with a heat exchanger and/or produce the cooling energy with an absorption chiller, the lack of heat must be provided by the auxiliary boiler. In contrast, the heat demand is first satisfied by the power generation unit for the FTL operation strategy. Some scholars have implemented studies and analyses about the operation strategies. Smith et al. [9] displayed the effects of thermodynamic system under different operation strategies with the input and model date uncertainty. To reach the energy-saving and economy-feasibility goals of the CCHP system, a feed-in tariff policy was proposed by Zheng et al. [8]. Wang et al. [10] presented the part-load performance of a trigeneration system for a hotel under different operation strategies. The calculation results demonstrated that different operation strategies were applicable to different types of building loads. The comparison between the heat dumping and load partialization using heat-driven operation strategy for residential natural gas-fired combined heating and power system were presented in [11]. Yang et al. [12] proposed a gas turbine-based CCHP combined with solar and compressed air energy storage for a hotel building under the FTL operation strategy. In addition, the selection of an operation strategy was affected by external factors such as the carbon tax or electricity feed in tariff [13].

Furthermore, some studies show that the FTL and FEL operation strategies may degrade much of the superior integrated performance of the system. Based on these operation strategies, other strategies have been proposed. Hajabdollahi et al. [14] presented the optimal design of the CCHP system and proposed a new operation strategy, where the cool-to-electricity ratio was adjusted. The results showed that the new strategy provided more benefit than the constant-ratio operation strategy for all studied climates. Analogously, Fang et al. [15] developed a complementary CCHP-ORC system, where the ratios of electric power to heat were adjustable for the requirements of users. To reduce the waste of electricity and heat improves the overall energy efficiency of the trigeneration system. A new operation strategy called hybrid electric-thermal load (FHL) was introduced in [16] and applied in [3,17]. In the literature [18], a new operation strategy on account of the minimum distance was proposed. Because of the satisfactory flexibility and adaptability, this strategy achieved better matching performance for a CCHP system than the FEL, FTL and FHL operation strategies. Basrawi et al. [19] analyzed the effects of different operation strategies on the economic and environmental performance on a CCHP system in a tropical region. Through studying multi-criteria evaluation, some conclusions were gained such as the Mix-Match and Power-Match operation strategies were preferred to generate positive net present value, and the Base-Load operation strategy was better for reducing all emissions. Moreover, several studies were completed to develop optimal operation strategy for energy system. The multi-criteria evaluation including COST, PEC and CDE were introduced to optimize the operation strategy of the CCHP for different climates [20].

The above literatures indicate that the performance of CCHP systems mainly depends on the operation strategies. Furthermore, the gas turbine is a critical component in the CCHP system. The part-load performance of the CCHP system is also affected by the alternative control methods of gas turbine. The control method for the gas turbine is an integral part for the selection of an appropriate operation of the CCHP system. Barelli et al. [21] analyzed an innovative supercharged gas turbine combined cycle with an accessional compressor upstream of the power generation unit. This system tended to be more efficient than the conventional configuration with a lower achievable load rate. The Ref. [22] focused on the part-load operations of a combined cycle to explore the possibilities for energy saving. Moreover, unlike the well-proven technology of the cooling inlet air for gas turbines [23], they demonstrated the benefits on the thermodynamic efficiency of this cycle obtained from the inlet air preheating. Analogously, an alternative operating strategy called flue gas reinjecting (FGR) for gas turbine on a CCHP system was proposed by Wang et al. [24]. The results indicated that improved energy utilization efficiency of the CCHP system was presented under combined FGR with TIT operating strategy. Moreover, the flue gas reinjection reduced excess air leading to the decrease of NO_X in the combustor and promoted the utilization of low-temperature surplus heat. The wet operation strategy of the micro gas turbine was also an alternative control method to accommodate the variable ratios of heat to electricity and decoupled power [25]. Furthermore, the variation of the inlet guide vane position was widely discussed in Refs. [26,27]. This control method reduced the mass flow of inlet air to maintain the exhaust gas temperature by varying the inlet guide vane position. The authors of [28,29] noted that a variable rotational speed operation enabled the decrease in output power without producing an excess in efficiency decay.

Han et al. [30] proposed and analyzed the inlet air throttling (IAT) control method for a gas turbine. The mass flow rate of the compressor

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