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Multi-objective assessment, optimization and application of a grid-connected combined cooling, heating and power system with compressed air energy storage and hybrid refrigeration

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ABSTRACT

As one of attractive technology of energy conservation, combined cooling, heating and power (CCHP) system has brought about widespread attention. However, the variability of users demand has limited the application of CCHP system. To ensure stable and efficient operation, the compressed air energy storage is considered to be integrated with CCHP system. A grid-connected CCHP system with compressed air energy storage (CAES) and hybrid refrigeration is proposed in this paper. The power from grid is stored in CAES at off-peak time and released at on-peak time. The hybrid refrigeration system including LiBr absorption chiller and electric compression refrigerator provides cooling load to users. A multi-objective assessment and optimization synthetically considering energy, economy and environment are presented. The multi-objective indicator used as objective function to optimize each component capacity of the proposed CCHP system. A sensitive analysis of key parameters and performance comparison with conventional CCHP system have been carried out. The results shows that when the capacity of gas turbine is 691 kW, the comprehensive performance of the proposed CCHP system is the optimal performance. The power price, natural gas price, compression ratio and turbine inlet temperature of CAES have great influence on the performance of the proposed CCHP system. Meanwhile, the multi-objective indicator's value of the proposed CCHP system is more than conventional CCHP system 4.85%.

1. Introduction

Due to rapid growth of population and economy, the energy shortage and environmental deterioration have become increasingly serious global problems. It is urgent to explore efficient technology of energy conservation, ensuring power supplies and reducing greenhouse gas emissions [1]. As one of most attractive energy efficient utilization technology, combined cooling, heating and power (CCHP) system has brought about widespread attention for energy saving, fuel independency, CO_2 emission reduction, business competitiveness, grid improvement [2–5]. However, the variability of users demand has limited the application of CCHP system [6]. The components capacity of CCHP system are usually installed to meet the maximum energy demand of users [7,8]. Due to the variability of users demand, each component of CCHP system operates under off-design condition for a long period, especially for prime mover, which may result in deterioration of thermodynamic performance and economy of the CCHP system [6]. Therefore, CCHP system integrated with electrical energy storage is being identified as one of solution to variability of users demand.

So far the available electrical energy storage technology mainly contains hydro storage, flywheel, compressed air energy storage (CAES), superconducting magnetic, secondary batteries, etc. Among those various electrical energy storage technologies, CAES is a promising method with high reliability, low environmental impact and economic feasibility [9–11]. Although numerous researches on CAES have been done, only two commercial CAES plants have been set up in the world [12]. The main reason is that large-scale CAES needs suitable underground geology, which limits its practical application. Therefore, micro-CAES using artificial air reservoir is a more adaptable and flexible measure for its wide application, especially for CCHP systems [13–15].

Recently, few efforts have been made by CCHP system integrated with CAES system only considering thermodynamic performance. Amin Mohammadi et al. studied the integration CAES with a combined cooling, heating and power cycle, which comprised of a gas turbine, an

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Nomenclature

Abbreviations

CAES	compressed air energy storage
CCHP	combined cooling, heating and power

Symbols

C	cost ($)
CE	CO_2 emission (kg)
CER	CO_2 emission reduction ratio
COP	coefficient of performance
CSR	total cost saving ratio
c	specific heat capacity (kJ/kg·K)
DTC	daily total cost ($)
i	interest rate
j	jth day of a year
k	air adiabatic exponent
LHV	lower calorific value of fuel (kJ/Nm^3)
MEI	multi-objective evaluation indicator
m	mass (kg)
$\dot{m}$	mass flow rate (kg/h)
n	life cycle of component (years)
P	power (kW)
$PESR$	primary energy saving ratio
p	pressure (MPa)
$\dot{Q}$	flux of heat (kW)
R	gas constant (kJ/kg·K)
T	temperature (K)
t	tth hour of day
V	volume (m^3)
α	CO_2 emission conversion factor of fuel
η	efficiency
ν	price ($/)
π	pressure ratio
ρ	density (kg/m^3)
τ	temperature ratio
ω	weighting factor

Subscripts

a	air
ab	LiBr absorption chiller
ac	air mass flow rate of compressor
at	air mass flow rate of turbine
b	boiler
CAR	compressed air reservoir
c	compressor
cl	cooling load
cs	charging stage
d	users demand
ec	electrical compression refrigerator
eco	economic
ene	energy
env	environmental
f	fuel
fg	flue gas
g	gas turbine
gab	generator of LiBr absorption chiller
h	heat
he	heat exchanger
he1	heat exchanger 1
he2	heat exchanger 2
he6	heat exchanger 6
i	investment
om	operation and maintenance
p	pressure
sg	separate generation system
t	turbine
0	ambient

organic Rankine cycle and an absorption refrigeration chiller. Energy and exergy analyses had been carried out. The results showed that the round trip energy efficiency was 53.94%, and the wind turbine, combustion chamber and compressed air storage system had the highest amount of exergy destruction respectively [16]. Based on the above, a new cogeneration system was furthermore presented by Sadreddini et al., including a CAES, an ORC cycle and ejector. The thermodynamic evaluation and effect of different parameters on the system performance had been investigated [17]. Zhang proposed hybrid distributed generation system integrated with CAES and thermal energy storage. The thermodynamic model of the system was built, and the thermodynamic performance analysis had been done. The results revealed that the hybrid system's exergy efficiency was 41.5%, and the primary fuel saving ratio was 23.13% [18]. Yang et al. proposed a gas turbine based CCHP combined with solar thermal energy and compressed air energy storage, the thermodynamic characteristics of the proposed system has been investigated [19]. In addition, the off-design performance of gas turbine-based CCHP system combined solar and compressed air energy storage with organic Rankine cycle had been carried out [20].

Actually, in addition to the thermodynamic performance, the performance of CCHP system is often related to economy and environment. Therefore, a comprehensive evaluation of CCHP system should be carried out, and optimization and design should be done to keep efficient operation of system. To obtain the optimum performance of a gas turbine based CCHP combined with solar and compressed air energy storage, Wang et al. performed a multi-objective optimization from the view of investment cost and exergy efficiency [21]. Yao et al. proposed a CCHP system based on small-scale CAES, multiple-objective optimization was adopted to find the trade-off between thermodynamic performance and total investment cost per total power output of the system [22]. Afterwards, Yao studied another CCHP system based compressed air energy storage system, including a gas turbine, an ammonia-water absorption refrigeration system and supplemental heat exchangers. The design trade-off between overall exergy efficiency and total specific cost of product was obtained by multi-objective optimization [23]. Jabari et al. presented a novel advanced adiabatic compressed air energy storage based CCHP system which was powered by a Stirling engine. A comprehensive energy and exergy based optimization were developed to minimize total energy procurement cost [24]. Yan et al. proposed hybrid CCHP system integrated with compressed air energy storage. Multi-objective optimization with the aim of minimizing the total cost and emissions had been accomplished [25].

From the aforementioned researches, the renewable energy was often used to driven CAES based on CCHP system to improve the energy efficiency of the system. The energy and economic factors had been taken into account during the course of optimization and design, seldom considering comprehensive factors which included energy, economic and environmental factors at the same time. In fact, the CCHP system is often connected to grid to ensure the system's operation in security. The power of grid is in short supply at on-peak time and in excessive supply at off-peak time. Moreover, the peak-valley time-of-use power price of grid is implemented. The power price at on-peak is expensive, and the power price at off-peak is inexpensive. Considering the characteristic of power supply and price, a grid-connected CCHP