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Multi-objective optimization of a gas turbine-based CCHP combined with solar and compressed air energy storage system

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ABSTRACT

The small-scale compressed air energy storage system (CAES) combined with renewable energy sources (RES) is becoming increasing popular in distributed energy system (DES), which allows RES uninterrupted and improves the supply capacity of power system. In order to balance the electricity load and improve the energy efficiency of CCHP system in combined cooling, heating and power (CCHP) system, the paper described a CCHP system combined with solar and compressed air energy storage (CCHP-S-CAES). Solar energy was coupled with the CAES in this paper to heat the high-pressure air from air storage cavern. The proposed system consists of a conventional CCHP, a CAES and a solar energy collector/storage system, which stores the surplus electric power of gas turbine during off-peak time and releases it during on-peak time. Sensitivity analysis on the CCHP-S-CAES system was conducted to investigate the effects of the key parameters on its performances. It is clear that the performances of the CCHP-S-CAES system are mainly determined by the pressure ratio of compressor, the inlet pressure and temperature of turbine and the effectiveness of heat exchangers. In addition, a multi-objective optimization based on the Non-dominated sorting Genetic Algorithm-II (NSGA-II) is performed for obtaining the optimum performance of the CCHP-S-CAES system from the view of investment cost and exergy efficiency. The results show that the optimal exergy efficiency of the proposed system is about 53.10% and 45.36% in maximum heating condition and maximum cooling condition respectively.

1. Introduction

During the past few decades, the risk and reality of environmental degradation and traditional fossil fuel depletion have become more apparent [1,2]. There is an urgent need for people to develop new renewable clean energy. As of 2014, renewable energy provided an estimated 19.2% of global final energy consumption. Wind energy and solar energy are two of the promising and rapidly developing renewable energy technologies. By the end of 2015, the global power capacity generated by wind energy and solar PV (photovoltaic) are 433 GW and 227 GW respectively [3]. However, the inherent instability and the intermittence of renewable energy cause a significant challenge to large-scale utilization [4].

Energy storage system is considered as one of the promising technologies which can solve the problems of fluctuations of renewable energy [5]. At present, the available energy storage system mainly includes pumped hydro storage, compressed air energy storage, secondary battery, superconducting magnetic energy storage system, flywheel and molten salt energy storage [6–11], etc. However, the compressed air energy storage system (CAES) is superior to other energy storage systems in longer lifetime, lower cost, and higher efficiency [12]. Besides, CAES is more perfected for large scale electric energy storage.

At present, two commercial CAES plants have been built, one is Huntorf plant of 290 MW, which has operated since 1978 in Germany; the other is McIntosh plant with 110 MW, which has operated since 1991 in America [13]. However, the existing CAES plants have some disadvantages such as their energy loss due to dissipation of heat of compression, use of fossil fuels, and dependence on geological formations. Therefore, some innovative concepts of CAES have been recently proposed [14].

Adriano [15] described an adiabatic compressed air energy system (A-CAES), which combined new thermal energy storage (TES) technology with CAES. The system achieves a round trip efficiency of approximately 70% with no fuel consumption. Guizzi [16] developed a liquid air energy storage system (LAES), which stores electrical energy in the form of liquid air instead of high-pressure air. The system can obtains a round-trip efficiency in the range of 54–55%. Najjar [17] analyzed the performances of compressed-air storage with humidification system (CASH). The results show that the primary energy efficiency

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Nomenclature

C	heat capacity rate (W/K)
c	specific heat at constant pressure [(kJ/kg·K)]
COP	coefficient of performance
$COST$	cost ($)
Ex	exergy value (kW)
ESR	energy saving ratio
h	enthalpy (kJ/kg)
$ICPP$	total investment cost per total output power (k$/kW)
K	ratio
LHV	net calorific value
m	mass flow rate (kg/s)
P	power (kW)
PLC	pressure loss coefficient
p	pressure (Mpa)
Q	heat rate (kW)
T	temperature (K)
W	work (kW)

Greek letters

δ	transmission loss
ε	effectiveness of heat exchanger
η	efficiency
π	pressure ratio; expansion ratio

Subscript

am	ambient
air	air
c	air compressor
cavern	air storage cavern
chill	LiBr/water absorption chiller
con	conventional separated system
cool	cooling energy
cp	charge process
cside	cool fluid
D	exergy destruction
ec	electric cooler
F	exergy fuel
fuel	fuel
grid	grid
GT	gas turbine
heat	heating energy
HRSG	heat recovery steam generator
hside	hot fluid
i	inner
in	inlet
max	maximum
min	minimum
oil	thermal oil
out	outlet
P	exergy product
pro	proposed system
solar	solar energy
t	air turbine
th	energy efficiency
tot	total exergy

Superscript

ch	chemical exergy
ph	physical exergy
s	isentropic
κ	adiabatic coefficient
*	normalized parameters

and the generated power of CASH are respectively about 9% and 14% more than those of conventional CAES. Park [18] presented an ocean compressed air energy storage (OCAES), using hydrostatic pressures in the deep ocean in order to keep compressed air at constant high pressure. However, these concepts about large-scale compressed air energy storage system are dependent on the right combination of site-dependent geological factors for air storage [19]. Thus, the small-scale compressed air energy storage (SS-CAES) with man-made air vessels has attracted more attentions.

SS-CAES could use artificial air reservoir without the restrictions of natural cavern, which is generally applied in a small distributed energy system, particularly in a building CCHP system. Recently, some new ideas about small-scale CAES coupled with CCHP have been put forward. Yan [20] proposed a CAES based hybrid CCHP system with renewable energies. In this system, the power generate unit is driven by biogas, meanwhile, wind turbine and photovoltaic cells are used to generate electricity to satisfy user demands and other equipments. The heat is produced by the compression heat of CAES is used for driving the absorption chiller and supplying heating load to user. The cooling load is provided by the absorption chiller and the expansion process of CAES. In addition, the thermal storage system and the gas boiler are introduced to store and supply the hot water respectively. He [21] presented a combined cooling, heating and power system combined with compressed air energy storage, which mainly consists of a gas turbine system and a CAES system. The authors found that a smaller scale gas turbine can be used for the same electric demand due to the integration of a CAES system. The results show that the gas turbine capacity of the proposed system was relatively 30.4% smaller than the conventional CCHP system. Yao [22] described a CCHP system based on a small-scale CAES. In this system, the compressor is driven by renewable energies during the off-peak time, while the compressed air is heated by the exhaust gas of gas engine, and then the compressed air drives the air turbine to produce electricity during the on-peak time. Mohammadi [23] proposed a CCHP coupled with energy turbine and CAES system, where, the most meaningful work is joined an organic Rankine cycle to CAES system for recovering the heat carried by turbine exhaust and producing more power.

Although several useful efforts have been made by the above mentioned CCHP combined with CAES systems, the problems of gas turbine low efficiency and power surplus due to the off-design working conditions of CCHP system still remains. Thus, this paper described a CCHP system combined with solar and compressed air energy storage based on the system presented by the authors [24], which is used for peak load shifting and balancing the electricity load. When the CCHP system operates under FTL mode, the gas turbine output power is not always matched with the power demand. If the former is greater than the latter, the surplus electric power drives the air compressor and stores the high-pressure air in air storage cavern. Conversely, the shortage of electric power has to be purchased from power grid. In actual operation, the energy loss occurs in the processes of energy storage and discharge due to the pressure loss; and also, power efficiency loss occurs in the discharge process due to the lower inlet temperature of air turbine in comparison with gas turbine. However, at a certain demand-side load distribution, the described system may improve the performances of gas turbine and enhances the electric power recovery of CCHP system, resulting from gas turbine load rate lifting and solar thermal energy utilization. Gas turbine load lifting also improves the performances of CCHP system, due to the efficiency