Energy 93 (2015) 1931–1942

Contents lists available at ScienceDirect

Energy

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

Performance analysis of energy storage system based on liquid carbon dioxide with different configurations

Mingkun Wang, Pan Zhao, Yi Yang, Yiping Dai*

Institute of Turbomachinery, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China

A R T I C L E I N F O

Article history:
Received 16 June 2015
Received in revised form
15 October 2015
Accepted 19 October 2015
Available online 19 November 2015

Keywords:
Wind power
Liquid carbon dioxide
Parametric analysis
Optimization analysis

A B S T R A C T

Due to the intermittence and fluctuation of wind resource, the increasing penetration level of wind power will bring huge challenges to maintain the stability of power system. In order to smooth the wind power output, additional controllable power from conventional power plant or energy storage system is required. In current paper, one basic scheme of liquid carbon dioxide storage system is proposed. The parametric analysis is conducted to examine the effect of some key thermodynamic parameters on the performance of this scheme. Subsequently, the basic scheme is improved according to the results. The mathematical models of two improved schemes are developed and the performance analyses are conducted. According to the results, the optimal scheme and configuration are determined. After optimization analysis and comparison analysis, compared to the other energy storage systems, the round trip efficiency of Scheme 3 is acceptable in consideration of the energy generated per unit volume of storage. As a conclusion, the optimal scheme has a good potential for storing wind power in large scale and offers an attractive solution to the challenges of the increasing penetration level of wind power.

1. Introduction

Increasing energy demand, shortage of fossil fuel resource and rising concern about environment protection have led to worldwide interests in exploitation of renewable energy sources. As a desirable renewable energy source, wind energy has been recognized as one of the most fast growing alternative power generation sources during the last few years. The rapid development of wind energy brings some huge challenges on power system stability and operation, especially in a high wind power penetration level [1,2]. Due to the intermittency of natural wind, wind energy is a type of non-dispatched and uncontrollable power sources. In order to smooth the wind power output, additional controllable power from conventional power plant or energy storage system is required. According to the different energy storage mechanism, the energy storage system can be divided into some categories, such as the PHS (pumped hydro storage system) [3], the CAES (compressed air energy storage system) [4], and the fuel cell energy storage system and other energy storage systems. In the current stage, only PHS and CAES can be selected as a massive energy storage system.

Pumped hydro energy storage is the oldest and most widely used method. A location with a suitable elevation gradient, and a large amount of storage media (water) are required to achieve large scale pumped hydro energy storage [5]. Compared to pumped hydro energy storage, CAES systems will require much less water and do not require a large elevation gradient.

CAES is one of the most promising storage technologies based on gas turbine technology. Due to the fuel dependency of the conventional CAES, several optimized CAES systems are proposed, such as the AA-CAES (advanced adiabatic compressed air energy storage) [6–8]. And energy storage hereby is performed by compressed air in caverns. These caverns can either be drilled in salt and rock formations or already existing cavities such as in aquifer strata, which make CAES and AA-CAES be restricted in application.

In order to overcome the restrictions of the CAES relying on the large storage cavern, some studies have been conducted on a novel energy storage technology based on liquid air. Variants of the LAES (liquid air energy storage) cycle were first described by Smith EM (1977). It shows there is a potential for greatly improving the storage efficiency by recovering cold heat from liquid air to utilize in a liquefaction process when liquid air is fed to gas turbine [9]. Kooichi et al. [10] proposed an energy storage system using liquid air with a simple and realizable cool storage unit which significantly increases the energy storage efficiency. Chen et al. [11] presented a supercritical

* Corresponding author. Tel.: +86 029 82668704; fax: +86 029 82668704.
E-mail address: ypdai@mail.xjtu.edu.cn (Y. Dai).

http://dx.doi.org/10.1016/j.energy.2015.10.075
0360-5442/

Nomenclature

W	power (kW)
m	mass flow rate (kg/s)
h	enthalpy (kJ/kg)
s	entropy (kJ/(kg·K))
I	exergy destruction (kW)
P	pressure (MPa)
T	temperature (K)
E	exergy (kW)
t	time (s)

Greek letters

η	efficiency

Subscript

0	ambient state
r245fa	organic fluid (R245fa)
wf	working fluid (CO_2)
com	compressor
TES	cool storage unit
TES1	heat storage unit
tur1-n	turbine 1-n
com1-n	compressor 1-n
Oil 1	cool oil
Oil 2	heat oil
con1	condenser 1
con2	condenser 2
orccon	ORC condenser
tur1	turbine 1
orctur	ORC turbine
pu1	pump 1
orcpu	ORC pump
eva	evaporator
ex	oil heat exchanger
in	inlet
out	outlet
char	the charge process
dischar	the discharge process
hs	heat side
cs	cool side

Acronyms

COP	compressor outlet pressure
COP1	compressor 1 outlet pressure
TOP	turbine 1 outlet pressure
ORC	Organic Rankine cycle
POP	pump 1 outlet pressure
RTE	round trip efficiency
EVR	energy generated per unit volume of storage

compressed air energy storage system based on the system proposed by Kooichi, in which the original liquefaction device-throttle valve is replaced by one expander, resulting in the increase of energy storage efficiency. Recently, several studies about LAES [12,13] have found that the liquid air energy storage system has a high energy density and no geographical restriction. However, the critical temperature of air is so low that the system needs good insulation equipment. Moreover, the cryogenic air and its vapor freeze human tissue rapidly and can cause many common materials to become brittle or even break under stress. Thus, the liquid air system exposes some potential hazards.

In recent years, the supercritical carbon dioxide cycle has attracted more and more attentions owing to its good properties and characteristics [14–16]. Compared to liquid air, carbon dioxide as the working fluid has the advantage of high critical temperature and is susceptible to liquefaction. Moreover, liquid carbon dioxide system has better safety and more flexibility. Therefore, a novel energy storage system is presented in this paper by combining liquid air energy storage system and supercritical carbon dioxide system. The proposed system, employs liquid carbon dioxide as its working fluid, not only overcomes the geographic restrictions of CAES and PHS, but also avoids that low temperature of liquid air(81.7 K) causes common materials to become brittle or even break under stress. In addition, as one novel energy storage technology, few studies have been carried out on the liquid carbon dioxide energy storage system. So it is meaningful to study the feasibility of this system, which can also expand the application of energy storage technologies.

In this paper, one basic scheme based on liquid carbon dioxide is proposed. Then two improved systems are presented and the mathematical models of those systems with different configurations are developed and implemented. Under different configurations, the parametric analyses are conducted to examine the effect of some key thermodynamic parameters on system performance. The goal of this work is to find the optimum configuration of this liquid carbon dioxide energy storage system, which can offer references for actual application.

The organization of this paper is as follows. Section 2 deals with the detailed presentation and the performance analysis of one basic scheme based on liquid carbon dioxide (Scheme 1). In Section 3, the basic scheme with ORC (Organic Rankine cycle) system (Scheme 2) is proposed and the performance analysis of this system is conducted. Section 4 deals with the detailed presentation of one improved system (Scheme 3), the performance analysis of this proposed system, and the comparison analysis among different technologies. And conclusions derived from simulation results are presented in Section 5.

2. Basic scheme (Scheme 1)

In order to reduce the negative effects of the wind power output fluctuations on the power system operation and stability, wind farm must be equipped with energy storage system. In this paper, one basic scheme based on liquid carbon dioxide is adopted as the energy storage system. Fig. 1 shows the basic scheme of a liquid carbon dioxide system. In this proposed system, the heat is transferred between charging process and discharging process by storing the thermal energy in heat transfer oil. The Cool storage unit is composed of steel pipes filled with a thermal storage medium such as small pebbles, which can meet the requirements of this system.

The effects of compression stage number and expansion stage number on the round trip efficiency were conducted. And in this part, the performance analysis of this system with multi-stage compression and multi-stage expansion is discussed, in order to obtain optimal combination of compression process and expansion process.

2.1. System overview

2.1.1. The charge process

As shown in Fig. 1, the working principle of the charge process is presented as follows: