Energy 77 (2014) 460–477

Contents lists available at ScienceDirect

Energy

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

Thermodynamic analysis of energy conversion and transfer in hybrid system consisting of wind turbine and advanced adiabatic compressed air energy storage

Yuan Zhang [a, b], Ke Yang [a, c, *], Xuemei Li [a, b], Jianzhong Xu [a, c]

[a] Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China
[b] University of The Chinese Academy of Sciences, Beijing 100190, China
[c] Key Laboratory of Wind Energy Utilization of The Chinese Academy of Sciences, Beijing 100190, China

ARTICLE INFO

Article history:
Received 17 December 2013
Received in revised form
9 September 2014
Accepted 12 September 2014
Available online 23 October 2014

Keywords:
Advanced adiabatic compressed air energy storage
Wind turbine
Hybrid system
Thermodynamic analysis
Energy conversion and transfer

ABSTRACT

A simulation model consisting of wind speed, wind turbine and AA-CAES (advanced adiabatic compressed air energy storage) system is developed in this paper, and thermodynamic analysis on energy conversion and transfer in hybrid system is carried out. The impacts of stable wind speed and unstable wind speed on the hybrid system are analyzed and compared from the viewpoint of energy conversion and system efficiency. Besides, energy conversion relationship between wind turbine and AA-CAES system is investigated on the basis of process analysis. The results show that there are several different forms of energy in hybrid system, which have distinct conversion relationship. As to wind turbine, power coefficient determines wind energy utilization efficiency, and in AA-CAES system, it is compressor efficiency that mainly affects energy conversion efficiencies of other components. The strength and fluctuation of wind speed have a direct impact on energy conversion efficiencies of components of hybrid system, and within proper wind speed scope, the maximum of system efficiency could be expected.

1. Introduction

With the exhaustion of traditional resources, wind power has been become an important part of energy utilization across the world [1]. However, the utilization of wind is hindered by its intermittent nature. The unbalance between the wind power and the demand of users has been recognized as an inevitable issue to deal with [2].

CAES (compressed air energy storage) technology is an accepted method to cope with the intermittence of wind power. Generally speaking, CAES is a high efficiency energy storage system based on gas turbine technology. During low demand periods, excess power is used to drive motor to compress air and compressed air is stored in air storage chamber; during peak load hours, compressed air is drawn from air storage chamber, then heated in a combustor and finally expanded through turbines to produce electricity [3]. It has been proven that CAES technology can optimize energy demand and supply, and decrease CO_2 emissions to some extent [4].

In recent years, the importance of wind power coupled with CAES has been given attention [5–9]. Energy output of wind turbine was evaluated from the perspective of thermodynamics by Rabbani et al., and energy storage was regarded as an effective technology to strengthen the utilization of wind energy and meet high load demand [5]. A hybrid system consisting of diesel engines and wind power was proposed by Ibrahim et al., and in order to reduce the use of fuel as well as maintain the stability of hybrid system, CAES was adopted to store excess wind energy [6]. Subsequently, optimization and sensitivity analysis of key parameters in the hybrid system were carried out for a higher utilization of wind power [7]. Drury et al. [8] developed a co-optimized CAES model, which is used to evaluate the effect of CAES on U.S. electricity markets. CAES and Adiabatic CAES technology were compared with each other from the economic point of view and Drury et al. concluded that modification of CAES was important to raise the revenues. The utilization of wind energy could be strengthened by CAES and hybrid system combined wind turbine with CAES was economically competitive with fossil fuel power plant in future [9].

* Corresponding author. Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China. Tel.: +86 10 82543038; fax: +86 10 82543037.
E-mail address: yangke@iet.cn (K. Yang).

http://dx.doi.org/10.1016/j.energy.2014.09.030

Nomenclature (Wind and wind turbine)

Wind

v_w	wind speed
v_{wB}	base wind speed
v_{wG}	gust wind speed
v_{wR}	ramp wind speed
v_{wN}	noise wind speed
K_B	constant
T_G	gust period
T_{1G}	gust starting time
v_{wGmax}	gust peak
v_{wRmax}	ramp maximum
T_{1R}	ramp starting time
T_{2R}	ramp stop time
T_R	ramp lasting time
T_{3R}	ramp end time
φ_i	random variable
$S_v(w_i)$	spectral density function
K_N	surface drag coefficient
F_s	turbulence scale
μ	mean speed of wind

Turbine

P_{wt}	output power of wind turbine
ρ	air density
R	rotor blade radius
v_w	wind speed
C_p	power coefficient of wind turbine
β	pitch angle
λ	tip speed ratio

Drive train

T_e	generator electrical torque
T_m	mechanical torque from generator shaft
ω_r	generator angular velocity
F	viscous friction coefficient
J_r	aerodynamic rotor inertia

DFIG

u_{dqs},u_{dqr}	two-phase stator and rotor voltages
R_s,R_r	per phase stator and rotor resistances
i_{dqs},i_{dqr}	two-phase stator and rotor currents
ψ_{dqs},ψ_{dq}	two-phase stator and rotor fluxes
ω_s	synchronous speed
ω_r	rotational speed of rotor
L_s, L_r	total cyclic stator and rotor inductances
L_m	magnetizing inductance
P_s, Q_s	active and reactive stator power
P_r, Q_r	active and reactive rotor power
n_p	number of pair poles

Nomenclature (AA-CAES system)

A	external surface area
E_x	exergy
G	mass flow rate
N	number of stages
P	rated power
Q	heat flow rate
R_g	gas constant
T	temperature
U	heat transfer coefficient
V	volume
W	total work
c	specific heat
c_p	constant pressure specific heat
c_v	constant volume specific heat
h	specific enthalpy
k	ratio of specific heats
m	mass
p	pressure
t	time
u	specific internal energy
w	specific work

Greek letters

α	coefficient about pressure
β	pressure ratio
τ	coefficient about mass flow rate
ε	heat exchanger effectiveness
η	efficiency
ρ	density

Subscripts

0	initial state
TES	Thermal energy storage
a	air
c	the compression process
e	the expansion process
g	generator
h	heat
m	motor
w	water
ac	air storage chamber
cs	isentropic process of compressor
ts	isentropic process of turbine
env	environment
in	enter
out	leave
min	minimum
max	maximum

Superscripts

in	enter
out	leave

Some scholars evaluated the effect of CAES on wind power from an economic view [10–13]. Madlener et al. [10] compared the economic feasibility of centralized with decentralized CAES for enhanced grid integration of wind power, then analyzed the revenue of Diabatic CAES and Adiabatic CAES system plant in electricity market. Optimization of wind turbine coupled with CAES was presented by Succar et al. [11], and they compared the advantage of hybrid system with stand-alone wind farm according to cost of electricity. Abbaspour et al. [12] analyzed optimal operation scheduling of wind power integrated with CAES technology on the basis of economic analysis.

Technical and economic analysis of a wind/CAES system in central Texas was carried out by Fertig et al. [13]. They pointed out the social benefits of wind/CAES and regarded that Adiabatic CAES has a better performance in future because Adiabatic CAES could eliminate the use of fossil fuel.