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Developing a grid-connected power optimization strategy for the integration of wind power with low-temperature adiabatic compressed air energy storage

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ABSTRACT

Compressed Air Energy Storage (CAES) is considered as one of the key solutions to handle intermittent and random wind power. However, limited energy conversion efficiency and high capital cost of energy storage have restricted significantly the integration of wind power with CAES. In this study, a grid-connected power optimization strategy based on piecewise averaging of real-time wind power and electricity price data is developed to ensure continuous and stable power outputs to the grid using modified profit-maximizing algorithm. Thermodynamic analysis on the performance of low-temperature adiabatic CAES, energy conversion, and economic evaluation were carried out for a hybrid wind/low-temperature adiabatic CAES system (wind/LA-CAES) with pressure vessels. The proposed optimization strategy reduced the required capacity of CAES and the levelized cost of electricity (LCOE) significantly with greater utilization of wind power and operation profitability. The findings presented in this study is of significant reference value to future development of large-scale wind power integrated with CAES.

1. Introduction

Wind power, as one of the most important renewable and clean energy resources, has increased in capacity globally over recent decades, because of the exhaustion of traditional resources and environmental degradation [1]. However, the widespread acceptance and use of wind energy are hindered by its intermittent and stochastic nature. For this reason, several techniques have been applied to deal with the instability problems, such as the pitch control of the wind power generator, wind power transfer through DC link and inverter control system, and energy storage [2,3]. Energy storage is considered as one of the most effective ways to handle the intermittence of wind power. In comparison with other types of energy storage, such as batteries, flywheels, and super-capacitors, CAES (compressed air energy storage) is a relatively established method of massive energy storage to deal with the instability of wind power at much less capital cost [4–9,48–51].

CAES is an energy storage technology that stores energy as high-pressure air. A number of studies have been carried out on various aspects of CAES. Detailed analysis and a summary of the development of CAES technology can be found in previous studies [10–15,52–54]. Thermodynamic analysis of adiabatic CAES with artificial reservoirs has been conducted to study the influence of heat transfer devices on system efficiency [11]. Moreover, Swider et al. investigated the operation and economic effect of CAES for large-scale wind power generation by a stochastic cost-minimization electricity market model for Germany [12]. Off-design analysis of two different discharge modes for CAES system was also conducted to improve energy conversion efficiency [13]. When this application was integrated with the wind power system, CAES balanced the output of wind power plant and reduced the peak and filling valleys of emergency reserve [5,14,16].

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Nomenclature

T, t	end of optimization period, time
Pm	piecewise wind power
Pg	grid-connected power output

Nomenclature (Low-temperature adiabatic CAES system)

T	temperature
η	efficiency
β	Pressure ratio
k	ratio of air specific heats
w	work consumption of unit mass
c_p	the specific heat capacity of air at constant pressure
W	total work consumption
m	mass
P_{shaft}	shaft power
ε	heat exchanger effectiveness
h	Specific enthalpy
u	Specific internal energy
G	mass flow rate
Q	heat transfer energy
W_t	technical work
e	specific energy
U	the heat transfer coefficient
p	pressure
V	volume
α	coefficient about pressure
τ	coefficient about mass flow rate
c_v	the constant volume specific heat
R_g	gas constant
E	exergy
$\overline{P}_T$	the average power output of the integrated system
P_c	Rated power of compressor train
P_e	Rated power of turbine train
Pew	Rated power of the wind turbine
C	investment cost
χ	levelized capital charge rate
Mf	the annual fixed operations and maintenance cost
M_v	the levelized variable operations and maintenance cost
h_y	the operating hours per year
yr	year

Superscripts

in	enter
out	leave

Subscripts

c	the compression process
cs	the isentropic process of compressor
w	water
e	the expansion process
ts	isentropic process of turbine
as	air storage
env	environment
h	high-temperature
wind	wind power
t	the turbine train
grid	grid-connected
LS	LA-CAES sub-system
IS	Integrated system
max	maximum
min	minimum
n	system component index
Turb	turbine train
Com	compressor train
a	annuity factor

The early concept for integrating wind power with large scale CAES was proposed by Cavallo et al., in 1995, which aimed to improve the capacity factor of wind turbine-transmission systems [17]. Subsequently, the economic feasibility of this system has been widely studied. The economic feasibility of a grid-connected hybrid wind-turbine and CAES system was investigated by Enis et al., which was based on above-ground compressed-air storage instead of large pressurized underground salt caverns [18]. A thorough economic analysis of hybrid wind/CAES systems was performed by Cavallo et al. who showed that controllable wind power with a CAES system was potentially affordable and economical in comparison with any nuclear or fossil fuel source power [19]. Fertig et al. presented a firm-level engineering-economic analysis of a wind/CAES system in Electric Reliability Council of Texas (ERCOT) under three scenarios, and they concluded that the current hybrid power system may be unprofitable at the firm-level without subsidies [20]. Loisel et al. investigated the economics of hybrid wind/CAES power system with a long-term market perspective of wind energy in France by using a technical and economic optimization model [21]. They found that it was economically feasible using price arbitrage and ancillary services that were provided to the power system to cover the additional storage cost of balancing the intermittency of wind power. In general, with increasing demand of wind power and by improving of CAES technology, there is no doubt that the integration of wind power with CAES is a feasible solution for large scale generation of wind power.

On the other hand, much attention was given to improve the performance of energy conversion and transfer efficiency of hybrid wind/CAES systems. Arise et al. used a thermo-economic model to study the energy management and optimization of the hybrid power plant, which attempted to match fluctuating power demand under unpredictable variability [22]. Succar et al. presented a methodology for combination optimization of the wind turbine specific rating and the storage capacity for a large-scale wind power plant integrated with compressed air energy storage, and resulted in a reduction in storage requirements by using lower rated wind turbines [23]. Saadat et al. developed a novel CAES system to downsize the electrical components in offshore wind turbine, which stored excess energy in a high pressure dual chamber liquid-compressed air vessel [24]. Hasan et al. proposed a parallel connected hybrid wind/CAES system to improve the power grid performance of wind power by a flexible output management of fluctuating wind power with the help of CAES system [25]. A novel hybrid wind-solar-CAES system was proposed by Ji et al. to improve the efficiency of electric energy storage, and the results showed that an optimum value as high as of 87.7% could be reached [26]. Recently, a small-scale hybrid wind turbine and CAES system with a mechanical power split device was proposed and validated using a laboratory-scale experiment test rig by Krupke et al. [27]. Table 1 is a summary of existing studies on hybrid wind/CAES system.

Typically, there are two types of hybrid wind/CAES systems: serial integration [28,29] and parallel integration [25,30]. In serial