Applied Energy 228 (2018) 1198–1219

Contents lists available at ScienceDirect

Applied Energy

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

Feasibility study of a simulation software tool development for dynamic modelling and transient control of adiabatic compressed air energy storage with its electrical power system applications

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HIGHLIGHTS

- A simulation tool for dynamic modelling and transient control of adiabatic CAES is presented.
- The structure of the simulation tool with a developed component library is introduced.
- Multi-physical models covers pneumatics, thermodynamics, turbomachinery and electrics.
- Case studies show its merits, e.g., performance analysis, dynamic control and grid applications.

ARTICLE INFO

Keywords:
Adiabatic compressed air energy storage
Thermal energy storage
Simulation software tool
Time-dependent dynamic modelling
Transient control
Electrical power system

ABSTRACT

The field of large-scale electrical energy storage is growing rapidly in both academia and industry, which has driven a fast increase in the research and development on adiabatic compressed air energy storage. The significant challenge of adiabatic compressed air energy storage with its thermal energy storage is in the complexity of the system dynamic characteristics arising from the multi-physical (pneumatic, thermal, mechanical and electrical) processes. This has led to a strong demand for simulation software tools specifically for dynamic modelling and transient control of relevant multi-scale components, subsystems and whole systems with different configurations. The paper presents a feasibility study of a simulation tool development implemented by the University of Warwick Engineering team to achieve this purpose. The developed tool includes a range of validated simulation models from the fields of pneumatics, thermodynamics, heat transfer, electrical machines and power grids. The structure of the developed tool is introduced and a component library is built up on the Matlab/Simulink platform. The mathematical descriptions of key components are presented, which precedes a presentation of four case studies of different applications. The case studies demonstrate that the simulation software tool can be used for dynamic modelling of multi-scale adiabatic compressed air energy storage components and systems, real performance analysis, dynamic control strategy implementation and feasibility studies of applications of adiabatic compressed air energy storage integrated with power grids. The paper concludes that the continued development and use of such a tool is both feasible and valuable.

1. Introduction

Electrical Energy Storage (EES) has been recognized as one of the significant technologies for solving great challenges in modern power systems, e.g., the network's reliability with a rapid increase of intermittent renewable energy generation. Among all EES technologies, Pumped Hydroelectric Storage (PHS) is a technology with high technical maturity and large energy/power capacity, which dominates the worldwide EES bulk storage capacity [1,2]. Apart from PHS, Compressed Air Energy Storage (CAES) is another commercialized technology with bulk storage capacity, which can offer both technical and economic benefits in different stages of power networks (e.g. generation, transmission, and distribution) with multi-scales (from a few kW to over 100 MW) [1,2]. It is proven that CAES has many outstanding advantages, such as large-scale availability, low operation cost, long lifetime and established industrial experience [1,2].

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https://doi.org/10.1016/j.apenergy.2018.06.068
Received 10 March 2018; Received in revised form 18 May 2018; Accepted 15 June 2018
0306-2619/

The working principle of a conventional CAES plant can be described as follows. During the charging (compression) mode, the electrical energy from the grid is used to drive a multi-stage compressor unit to compress the air into a storage reservoir. To improve the efficiency of the compression process, the compressor unit normally uses coolers to reduce the air temperature after each stage of compression [1,2]. Also, for large-scale CAES plants, only underground salt cavens have practical commercial operation experience for the purpose of storing a large amount of compressed air [2,3]. During the discharging (expansion) mode, the stored compressed air with high pressures is released, heated by fossil fuel combustion, and then expanded via a multi-stage turbine (or expander). Finally the electricity is generated by an electrical generator connected to the main shaft of the turbine. Two large-scale conventional CAES plants are in commercial operation worldwide, that is, 290 MW/580 MWh German Huntorf CAES plant and 110 MW/2860 MWh US McIntosh CAES plant. Both of them use the combustion of natural gas to heat compressed air for electricity generation [2,3].

With the development of technology, the concept of adiabatic CAES (i.e., a hybrid combination of CAES and Thermal Energy Storage (TES) without involving fossil fuel combustion), has received much attention. In a conventional CAES plant, a large amount of heat generated from the charging (compression) mode is directly released to the atmosphere via the cooler operation, which is a waste of useful energy. Adiabatic CAES can store and reuse this heat energy in the CAES discharging (expansion) mode for enhancing the compressed air energy with high temperature to generate electricity [4–6]. This concept increases the complexity of the whole system because the closed loop of the heat transfer medium to TES (including heat exchange and thermal storage units) must have the capacities and the performance to match the requirements of the air compression/expansion units. The key features of adiabatic CAES include: (1) improving the cycle efficiency of the overall system, i.e., the cycle efficiency of adiabatic CAES could be up to around 70%, compared to Huntorf (42%) and McIntosh (54%); (2) avoiding the use of fossil fuels in CAES discharging (expansion) modes, which is a significant advantage over the conventional CAES plants [1,2].

Some demonstration plants using adiabatic CAES technology have recently been built or are under construction. A multi-stage regenerative 500 kW demonstration system (named “TICC-500”), designed jointly by Tsinghua University, Institute of Physics and Chemistry of Chinese Academy of Science and China Electric Power Research Institute, had its trial interconnection with the Chinese power grid in 2014 [2]. A 1.5 MW supercritical adiabatic CAES demonstration system designed by Institute of Engineering Thermophysics of Chinese Academy of Science with its academic and industrial partners has been operating for more than 3000 h since its first test, running from 2014 [2,7]. The compressed air in a part of the air circuit of the system is at its supercritical state and the system cycle efficiency can achieve about 55% [2,7]. Based on this experience, Institute of Engineering Thermophysics of Chinese Academy of Science has leaded another project – the first 10 MW adiabatic CAES demonstration project in China, which has started its test running in 2017 [2]. In Germany, it was claimed that the world’s first large-scale adiabatic CAES project named ADELE has been designed by RWE Power, General Electric, Zűblin and DLR [8]. The targets of the project are: (1) adiabatic CAES combining other individual energy sources (especially wind power) to achieve electrical energy storage completely without CO_2 emissions, with 70% cycle efficiency; (2) the project has planed to have a storage capacity of 360 MWh and a power output of 90 MW [8]. However, the project is currently on hold due to uncertain business conditions [2].

Academic researchers have explored the concept of adiabatic CAES with a range of different research focuses, such as simulation modelling, efficiency analysis and configuration optimisation. Luo et al. presented an adiabatic CAES system model with a time-dependent dynamic model for the compressed air storage and thermodynamic (steady state) models for other components in the system (compressors, expanders, valves and pumps) [9]. Liquid water was used as a heat transfer medium and for heat storage. The paper also reported a system parametric study and optimised the system’s configuration [9]. Hartmann et al. studied the simulation analysis of different adiabatic CAES plant configurations [6]. The models of compressors and turbines were based on the thermodynamic state equations of the polytropic and isentropic processes. The study concluded that the efficiency of the polytropic configuration was about 60%, and 70% efficiency could reach when choosing the isentropic (ideal) configuration [6]. Guo et al. studied a similar mathematical model for adiabatic CAES [10]. A simulation study on the cycle efficiency and the energy storage density was carried out [10]. Wolf and Budt presented a techno-economic analysis of a low-temperature adiabatic CAES system and a simple thermodynamic description of the system was employed [5]. The theoretical study indicated that the cycle efficiency is in the range of 52–60% with wide-ranging part load capabilities [5]. Chen et al. presented an isobaric adiabatic CAES system, in which CO_2 and its mixtures are used as the volatile fluids for extending the system operation over a wide range of ambient temperatures [11]. The thermodynamic analysis, including exergy efficiency analysis and a parametric analysis, was evaluated based on the developed steady state model [11]. Wang et al. experimentally studied a pilot CAES system with TES, which used water as the TES working medium and heat storage [12]. An average cycle efficiency of 22.6% was achieved in the tests [12]. The paper discussed the reasons for such a low efficiency: (1) the unsteady operation of the compressor caused by the pressure variation in the storage tank; (2) the output electric generator operating at its off-design conditions; (3) the non-optimal performance of the TES subsystem [12]. These findings show the importance of dynamic control strategy development and implementation using a complete system (electricity-to-electricity) dynamic model for improving the cycle efficiency. Peng et al. studied the thermodynamic performance of an adiabatic CAES system with a Packed Bed Thermal Energy Storage (PBTES) subsystem [4]. The thermal behaviour of PBTES was studied and then an updated A-CAES system with a heat recuperator was further proposed to improve the cycle efficiency. An exergy analysis performed by Barbour et al. indicated that the main losses for adiabatic CAES with PBTES occur in the compressors and expanders [13]. Both papers [4,13] focused on the dynamic modelling of PBTES. In Sciacovelli et al.’s model [14] (except for the compressed air reservoirs and PBTES) the compressors, turbines and heat exchangers used steady state modelling methodologies (thermodynamic and Number of Heat Transfer (NTU) modelling methods). Thus the dynamic control strategies cannot be studied by using the developed system model. Although the paper claimed that the study linked the component performance and the plant performance, no electrical modelling (e.g. electric motors/generators/loads) was considered [14]. He et al. studied a cycle-to-cycle modelling framework to simulate adiabatic CAES with PBTES [15]. Phase Change Material (PCM) filled PBTES and rock filled PBTES were studied respectively. The paper mainly focused on the study of thermodynamic variables (e.g., pressure, flow rate and temperature) and the cycle efficiency analysis, while most mechanical and electrical variables (e.g., compressor torque and generator voltage/current) were not discussed. Tola et al. proposed a system configuration including axial compressors, radial and axial turbines and a PBTES subsystem [16]. The article only presented a simple PBTES mathematical model. A simulation study including a cycle efficiency analysis was carried out, considering the off-design working conditions [16]. In addition, a few overview papers focused on CAES technology development were recently published [2,17–19], and all of them have introduced the adiabatic CAES concept and its state of the art.

From the above research papers (i.e., [4–6,9–16], almost all of the modelling approaches used one or more thermodynamic (steady state) submodels (e.g., the submodels of compressors and expanders/turbines), and none considered detailed submodels of relevant electrical