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New radial turbine dynamic modelling in a low-temperature adiabatic compressed air energy storage system discharging process

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ABSTRACT

It is challenging to gain insight of a Compressed Air Energy Storage (CAES) system dynamic behaviour under various operation conditions due to its complexity with mixed mechanical, thermal, chemical and electrical processes in one. Although a number of studies are reported on CAES steady state and dynamic modelling to reveal its characteristics, few studies have been reported in whole CAES system dynamic modelling involving a radial turbine. This paper explores a new method to analyse the transient performance of the radial turbine while it is integrated with whole low temperature Adiabatic-CAES system. The proposed modelling method approximates the average air flow within single stator/rotor stage. By applying the principle of energy and torque balance on the transmission shaft, the dynamic speed-torque characteristics of the turbine is obtained with a "quasi dynamic iterative searching" process. The model is then integrated to a simulation platform, which is created to synchronise the wide range of time scale dynamic responses including heat transfer, mechanical and electrical energy conversion processes. As every component of the low temperature adiabatic CAES system is built on its fundamental physical and engineering principles, the model is capable of revealing the system transient characteristics. Based on the model, various simulation studies are conducted and the results are compared with the operation data from the literature. It provides a valuable tool for preliminary design of a radial turbine to test its suitability in full and partial load operation conditions, and analyse its transient behaviours.

1. Introduction

Energy storage recently attracts great attentions in addressing the issues associated with rapid growth of power generation from intermittent renewable energy sources. Among various technologies for electrical energy storage, Compressed Air Energy Storage (CAES) is one of two proven technologies suitable for building large-scale plants (over 100 MW). There are two successfully operated CAES plants in the world. The first utility-scale CAES is the 290 MW Huntorf plant in Germany using salt dome for air storage, which was built in 1978. The other is an 110 MW plant with a capacity of 26 h in McIntosh, Alabama, USA. The common feature of the two CAES plants is that they both require fossil fuels to achieve its rated power. To avoid consuming the fossil fuels, adiabatic CAES (A-CAES) with Thermal Energy Storage (TES) become a new technology development direction.

Wolf and Budt proposed a low-temperature A-CAES (LTA-CAES) using multi-stage radial compressors and expanders, in which operational temperature of heat storage was between 95 and 200 °C [1]. According to their analysis, advantages of the LTA-CAES include the fast start-up characteristics, wide-ranging part load, highly available thermal working fluid, low pressure drop of compressed air and potential plant profitability [1]. Luo et al. also studied a LTA-CAES system and indicated the cycle efficiency and heat energy recycle efficiency can reach around 68% and 60%, respectively [2]. With the acceptable cycle efficiency, potential operational flexibility of the LTA-CAES plant makes it a promising and feasible solution. But recently, Wang et al. presented the first public experiment on a LTA-CAES system [3]. Although the feasibility of the LTA-CAES was demonstrated in practice, only an averaged cycle efficiency of 22.6% was achieved in the pilot "TICC-500" plant [3]. The low efficiency was mainly caused by the nature of the transient system operation of the A-CAES system in realistic operations, which reduced the efficiency of components when they were operated from their design conditions.

From the published literature, previous investigations developed dynamic analysis of CAES systems with volume-based expanders. Sun et al. developed a complete dynamic mathematical model of a hybrid

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CAES-wind turbine system, in which a scroll machine is selected for expanding the compressed air [4]. Krupke et al. further demonstrated the benefits of improved efficiency and flexibility brought to the wind turbine by the hybridization with a scroll expander based CAES system to smooth the time variant fluctuations [5]. Compared to the volume-based expanders, prior studies about the turbine-based CAES system mainly focused on steady-state thermodynamic analysis. Liu and Wang thermodynamically analysed a modified A-CAES system using steady-state mathematical models of turbines, and found 3% exergy efficiency increase [6]. Yao et al. searched for the Pareto front of a small-scale turbine-based CAES system between thermodynamic and economic performance [7]. Guo et al. proposed a CAES system integrated with ejector technology and indicated a 3.41% efficiency increase by thermodynamic analysis [8]. Particularly, the radial turbine is recognised for high efficiency and light weight in high power capacity compared to volume based expanders. The power rating of a radial turbine is usually up to several megawatts [9], and thus, it has great potential in small-scale and medium-scale CAES systems. But the radial turbines usually have low efficiency in off-design operations [10]. As a consequence, evaluating the off-design operations' performance and the transitions of the CAES system with the radial turbine become particularly important due to the varied performance of the radial turbine and the complex interactions between the component and system.

However, there are very limited studies that addressed the dynamic characteristics of turbines. Arabkoohsar et al. considered the off-design performance of compressors/turbines using an empirical relation in the steady-state thermodynamic modelling [11]. Wolf dynamically simulated a high-temperature A-CAES system in which main system response was dominated by the heat storage and turbines were modelled using empirical polynomial models [12]. Similarly, Sciacovelli et al. investigated how packed bed heat storage dynamics inducing off-design conditions of turbines [13], but mechanical responses of turbines were not resolved. Li et al. only corrected the mass flow rate of the air turbine under off-design conditions in an integrated system of a diesel genset and a CAES unit [14]. Zhao et al. selected two operational modes of the CAES system and carried out the off-design operational analysis in different power levels and speed levels [15], in which each operation (100% load or partial load) was considered as the static operation. Briola et al. used the experimental characteristic curves as the basis and predicted the operative behaviour of turbomachines over a wider range of conditions by the affine transformation method [16].

The complexity of turbine-generator rig dynamics is resulted from the multiple conversions between air momentum/potentials, mechanical and electrical energy. Therefore, a new "quasi dynamic iterative searching" method for modelling turbine dynamic behaviours is proposed in this study, aiming to understand the dynamic characteristics of turbines in a LTA-CAES operation cycle. The turbine dynamic changes is derived in response to the mechanical shaft dynamics which the turbine is connected to and the mechanical-electrical energy conversion happens through, by decoupling the air mass and momentum inside the turbine flow path as purely flow resistive [17]. This shaft dynamic response repeats every numerical step iteratively. The mean-line model is adopted to generate the characteristic equations of the turbine which are used for iterative searching of the balance states to match the shaft dynamic variations at every time-step. This model is built on the knowledge of the turbines' geometry, e.g. size of stator/rotor, to generate the characteristic curves of turbomachinery in various operational loads.

Furthermore, the LTA-CAES system has dynamically coupled components and wide variations of component dynamic response time scales. It is crucial to have simulation models accurate enough for main components. With these models, the assembled whole system model can reveal the system dynamic responses under various operation conditions and parameters. Therefore, this study starts from the key component (radial turbines) modelling and verification to the whole LTA-CAES system with integration of the turbines. A new "quasi dynamic iterative searching" method is proposed to reflect both the off-design operative behaviours and dynamic characteristics of the radial turbine in the LTA-CAES system. In addition to the radial turbines, the associated component models are also introduced which include heat exchanger (HEX), air storage, sensible thermal storage, and generator. The feasibility of the dynamic modelling methodology is investigated by comparing the simulation results with the published experimental data. Then, with the validated modelling method, effects of HEX's design are evaluated, and a case study is presented in the paper to reveal the start-up and operation transitions of the LTA-CAES system and radial turbines between design and off-design operations.

2. System configuration: discharge process of the low temperature adiabatic compressed air energy storage

The system configuration considered in this study utilises the latest pilot A-CAES plant named "TICC-500", which is built by the Key Laboratory of Cryogenics, Chinese Academy of Science [3]. The maximum output power of the generator is designed to be 500 kW. The pilot plant has five compression stages with inter-cooling and three expansion stages with inter-heating. The TES system employs pressurised water as the thermal fluid. Particularly in the discharge period, as shown in Fig. 1, pressurised water from the hot water tank heats up compressed air from the air storage tank in the HEX before the air flowing into the turbine stages. Then, energy from the reheated compressed air is converted to the mechanical energy of the rotating turbines. The cooled water flows to the cold water tank which stores the cold for cooling down the compressed air during the charge period.

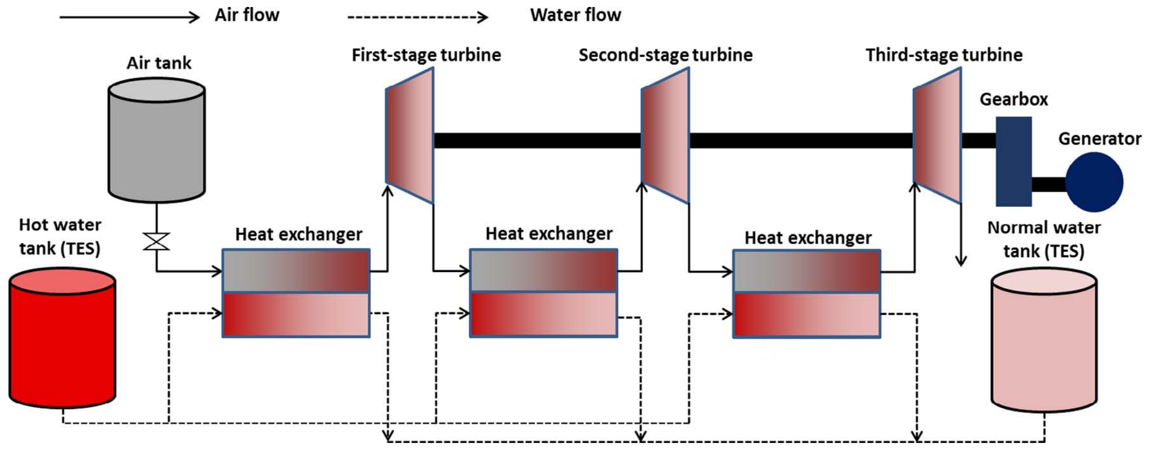

Fig. 1. Schematic diagram of the studied LTA-CAES discharge system.