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Optimal selection of air expansion machine in Compressed Air Energy Storage: A review

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A R T I C L E I N F O

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A B S T R A C T

Electrical energy storage has been recognised as an underpinning technology to meet the challenges in the power network arisen from the rapidly increasing penetration of renewable energy. Compressed Air Energy Storage (CAES) has gained substantial worldwide attention in recent years due to its low-cost and high-reliability in the large-scale energy storage systems. Air expander is one of the key components in a CAES system because its operational characteristics determine the power conversion efficiency and the power generation during the discharge period. The performance of the expander contributes heavily to the round trip efficiency of the whole system. This paper presents an up-to-date review of the CAES technology, and methods for modelling and selecting expanders for CAES systems. The focuses of selecting the appropriate expansion machines are identifying and analysing the characteristics of both CAES systems and expansion machines, and finding the matched expanders for the CAES system formulation (i.e. diabatic, adiabatic and isothermal CAES) and operational conditions (i.e. air pressure, temperature and flow rate). After all, recommendations and guidelines in selecting appropriate expanders and expansion stage numbers are formulated and discussed; this laid a step stone for choosing suitable expansion machines to achieve an overall CAES system high efficiency.

1. Introduction

Carbon dioxide emission, one of the major causes for global warming, has been recognised as a pressing issue and needs to be tackled in this generation [1]. To address this issue, reducing use of fossil fuels is unavoidable, which calls for power generation from renewable energy sources to meet the electricity demand. It has been evidenced by the rapidly increased penetration of renewable energy to the power network in recent years [2–5]. In 2014, power from renewable energies represented approximately 58.5% of the net additions to the global power generation capacity, with considerable growths in all regions [6]. By the end of 2014, renewables, mainly wind, solar PV and hydro power, accounted for an estimated 27.7% of the world's power generation capacity, enough to supply 22.8% of global electricity [6]. However, due to the inherent intermittence of the most renewable energy sources, there is a great challenge in the power generation and load balance to maintain the stability and reliability of the power network [7]. While various solutions are sought, energy storage has been recognised as one of the feasible technologies to address these issues, which facilitates the power balancing by decoupling the generation and consumption in the time and space domains through multiple charging and discharging cycles [8].

Based on the form of energy stored in the system, major energy storage technologies include mechanical (pumped hydro, compressed air, and flywheel), electrochemical (batteries), electrical (capacitors), chemical (hydrogen with fuel cells), and thermal energy storage. Technical characteristics of the selected energy storage technologies are listed in Table 1. Mechanical storage systems, has long lifetime, low energy capital cost, and much larger power/energy rating than other energy storage technologies listed in Table 1. Therefore, they are suitable for time shifting, load shaving, load levelling, and seasonal energy storage. As one of the two large-scale commercialised energy storage technologies, large-scale commercialised Compressed Air Energy Storage (CAES) plants which are able to provide rated power capacity over 100 MW by single generation unit, have demonstrate to be reliable in the large-scale energy management [9].

Because the maturity of Pumped Hydro Energy Storage (PHES), the PHES plants have been deployed worldwide. However, these commercialised large-scale plant are subject to severe geographic restrictions. A site for a PHS plant must be suitable for the construction of standing or dammed-up water reservoirs with very large volumes for storing water [10]. In fact, the number of installation of new PHES plants has inclined

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Table 1
Characteristics of several energy storage technologies. These characteristics listed in the table are summarised from the review and comparisons in [23].

Characteristics	Large-scale CAES	Small CAES	PHES	Li-ion battery	Lead acid battery	Super-capacity	Hydrogen fuel
Power density, W/L	0.5–2	> large-scale CAES	0.5–1.5	1500–10,000	10–400	> 100,000	> 500
Energy density, Wh/L	2–6	> large-scale CAES	0.5–2	200–500	50–90	10–30	500–3000
Rated power rating, MW	100–1000	0.003–3 potential to 10	100–5000	0–100	0–40	0–0.3+	< 50
Rated energy capacity, MWh	< 1000	< ~ 0.01	500–8000	0–10	0–40	0–0.0005	0.312 and 39
Lifetime, year	20–40	> 23	40–60	5–16	5–15	10–30	5–20
Cycle efficiency	40–70%	–	70–85%	75–97%	63–90%	84–95%	20–66%
Response time	Minutes	Seconds-minutes	Minutes	Milli-seconds	Milli-seconds	Milli-seconds	Seconds
Power capital cost, $/kWh	400–1000	517–1550	2000–4000	900–4000	300–600	100–450	500–3000
Energy capital cost, $/kWh	2–120	200–250	5–100	600–3800	200–400	300–2000	2–15

since 90's due to the environmental concerns and the scarcity of favourable sites [11]. The potential for the further major PHES schemes would also be restricted [12]. Different from the PHES plant, in a CAES system, air, instead of water, is compressed and released by compressors and expanders to fulfil a cycle of charge and discharge [13]. Although the large-scale storage of the compressed air is also restricted by geologic conditions, there are much more available sites for a large-scale CAES plant than the available sites for PHES. Porous rock reservoirs (aquifers or existing depleted gas reservoirs) and cavern reservoirs (caverns in salt formation and low-permeability hard rock) are appropriate for CAES. For example, existing gas storage facilities for natural gas storage might be suitable for storing compressed air [14].

Excluding the successful applications in the large-scale energy storage, with the continuous development of CAES, small-scale systems of CAES are also explored in both academic studies and industrial projects [15–18]. Prototypes of micro-scale and small-scale CAES systems emerged as the alternatives to the electrical or electrochemistry based energy storage technologies, such as batteries [19] and super-capacitors [20]. To compete with the well-developed high energy/power density electrical and electrochemical energy storage technologies as listed in Table 1, small scale CAES systems have several advantages, such as low self-discharge, long life-time, low-maintenance, reliable even in hostile environments, etc. Although there are several published reviews of energy storage systems in which potential benefits of CAES have been recognised [21–24], and a recent overview on CAES history and system classification [25], limited studies were reported on the optimal selection of the CAES system components. Most recently, Marvania and Subudhi presented a comprehensive review of compressed air power engines for vehicles in which the propulsion system is quite similar to CAES [26]. Nevertheless, the power capacity and energy density of the compressed air power engines are limited and significantly smaller than those used in many CAES systems.

In a CAES system, the expander is a critical component in determining the rated power output and the overall energy conversion efficiency. The selection of expanders in formulating a CAES system highly depends on both the system operations and the discharge power capacity of the energy storage system [27]. Generally, two main types of expanders can be distinguished from the market: the positive displacement (volume) type, such as reciprocating expander, screw and scroll expanders, and the dynamic (velocity) types, such as radial and axial turbines. To select an appropriate expansion machine, several reviews of applications and guidelines of different expansion machines have been reported in the studies of organic Rankine cycle (ORC). Qiu et al. reviewed various expansion machines and discussed the principles of selecting different types of expanders for ORC-based micro-CHP (combined heat and power) systems [28]. Bao and Zhao discussed all types of expansion machines' operating characteristics, aimed to guide the selection of expanders for an efficient ORC system [29]. Lemort et al. compared different expansion machines, especially for the positive displacement types including reciprocating, screw and scroll expanders, in ORC systems with different working fluids [30–34].

Compared to heat engines such as ORC, CAES has its unique characterisations: 1) air is the working fluid to fulfil the charge and discharge processes; 2) compared to heat engines which generate electricity between two heat sources, the potential of air, i.e. air pressure, plays a much significant role in CAES; and 3) CAES systems charge and discharge associating with multiple heat sources in a variety of ways. Therefore, although the experiences from the design of expanders in traditional heat engine cycles are beneficial, specific considerations and requirements for expander's design are needed for different CAES system types. However, from the published literatures, there is lack of guidelines on selection of expansion machines to fit and match the CAES system formulations. To fill the knowledge gap and enable optimal selection and design of expanders in CAES, tools for simulations of a CAES system considering the expanders' geometric parameters are essential. Rather than general thermodynamic analysis, requirements for a expander model used in CAES system modelling are not only accurate sufficiently to present the characteristics of the expander at the component-level, but also efficient in computation and compatible to be integrated to a system-level simulation.

Therefore, this study aims to compare different expansion machines and their potential applications in CAES systems, and review the associated mathematical models which are suitable for a system-level modelling. In order to provide a state-of-the-art picture of CAES technology development and a guideline of selecting appropriate expansion machines in practice, this review covers: 1) an overview of CAES system types, and 2) a comparative discussion of expansion machine types and their applications in CAES systems. For deriving the principles for recommendations of expanders, classifications of the current CAES systems are introduced. According to the energy flow in a CAES system, three major types of CAES are discussed to form the fundamental principles in choosing appropriate expanders. Then, several machine types of expanders are briefly introduced, including both volumetric and dynamic types. Finally, recommendations of expanders subject to CAES system types and scales are made and a generic preliminary system/component design procedure is also discussed.

2. Overview and comparison of CAES system formulation

In general, a CAES system refers to a process of converting electrical energy to a form of compressed air for energy storage and then it is converted back to electricity when needed. An illustrated conventional CAES system is plotted in Fig. 1. During the charge process, air is pressurised by compressors which are driven by motors using off-peak electricity from the grid or/and renewable energy. Before the storage and the compression, the compressed air flows through interconnected heat exchangers or other heat sinks to decrease its temperature. During the discharge period, the compressed air is first heated by the heat exchangers or other heat sources and produce work by expanders. The mechanical work is converted to electricity by connecting electric generators to the expander's shaft. Five major sub-processes formulate a complete CAES system: 1) air compression; 2) heat exchanges during both charge and discharge; 3) air expansion; 4) compressed air storage in cavity or pressure container/tank; and 5) mechanical transmission