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Thermodynamic analysis of a hybrid thermal-compressed air energy storage system for the integration of wind power

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HIGHLIGHTS

- A novel concept of adiabatic compressed air energy storage is proposed.
- Heat TES using electricity heaters after TES absorbs heat from air.
- Power storage capacity of the new system can be greatly increased.
- Recovery efficiency of the wind power used for electric heating is about 41–47%.
- Power output increase is about 19–125% depending on the TES storage temperature.

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ABSTRACT

In China, a large amount of wind power is abandoned due to the difficulty of integrating fluctuating wind power into electricity grid systems. Advanced adiabatic compressed air energy storage (AA-CAES) is regarded as a promising emission-free technology to facilitate the wind power integration, but its high capital cost has hindered its wide commercialization. In the present work, a novel hybrid system was proposed on the basis of AA-CAES. It can reduce abandoned wind power and improve the financial return per capital cost of the system by increasing power output. In the new system, which is called hybrid thermal-compressed air energy storage (HTCAES), thermal energy storage (TES) units absorb the heat released from air compression and also the thermal energy converted from reluctant wind power using electrical heaters. Theoretical thermodynamic analyses show that the HTCAES system can absorb much more wind power than an AA-CAES system with the same scale of compressors, turbines, and TES units do. And recovery efficiency of this additional wind power is about 41–47%, depending on the final storage temperature of the TES. The power output ratio of the HTCAES system to the AA-CAES system increases with the maximum TES storage temperature and decreases with the operating pressure.

1. Introduction

The past decade has seen a rapid increase of wind power installation in China because compared with other kinds of renewable energy, wind power has good economy and mature technologies. Studies show that the installed capacity of wind power in China increased 167 times from 2002 to 2012 [1]. As this trend continues, the integration of wind power into the electricity grid systems becomes more and more challenging due to the intermittent nature of wind [2,3]. In 2012, 19.8% of the total wind power in China was abandoned for the safety of electricity grid systems, leading to a great economical loss. One of the most promising solutions to this problem is to combine large-scale energy storage technologies with wind power generators [4–6]. Energy storage systems can store reluctant wind power when the electricity demand is low and release it during the peak-time of electricity consumption, thus enabling wind power to serve the base-load market [7–9].

Among various kinds of energy storage technologies [10–15], compressed air energy storage (CAES) and pumped hydro storage are the most viable ones for large scale storage applications. Comparing these two technologies, CAES has a lower capital and maintenance cost [7,16] and less geographic restrictions, which makes it more attractive. Currently, there are two types of CAES systems: diabatic and adiabatic CAES. In diabatic CAESs, thermal

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energy resulted from air compression is dissipated and fossil fuel is required to reheat the compressed air during discharge processes. While in advanced adiabatic CAESs (AA-CAESs) [17,18], thermal energy from air compression is stored in thermal energy storage (TES) units and returned back to the compressed air during discharge. Due to the advantages of higher overall efficiency and free carbon dioxide emission, AA-CAES is becoming more attractive, as the global climate change has gradually become a focused concern in the world.

However, the addition of TES units in AA-CAESs increases the system complexity and capital cost. So far, there are two diabatic CAES plants in operation (Huntorf, Germany and McIntosh, United States) but no adiabatic CAES plant was built. High capital cost is one of the main reasons that hindered the commercialization of AA-CAES systems. For TES units with solid energy storage media [17,18], expensive pressurized containers are required; while for those with liquid energy storage media [19–22], complicated and also expensive heat exchangers are involved. One of the measures to make AA-CAES more competitive is to develop advanced compressors with higher discharge temperatures [21]. Usually, when the operating pressure is higher than 30 bars, an AA-CAES system should at least have two stages of compressors to keep the discharge temperatures at the outlet of the compressors lower than a certain temperature limit. Currently, this temperature limit for industrial compressors is about 400 °C [21]. If advanced compressors with higher discharge temperatures are developed, the complexity of an AA-CAES system can be reduced. In addition, higher discharge temperature of compressor can lead to higher TES storage temperature and hence higher system efficiency [23]. However, the development of these advanced compressors requires significant prototype engineering development and the price of these compressors will be also expensive due to its technical difficultly and limited potential market [21].

The purpose of this paper is to propose a new concept of energy storage system on the basis of AA-CAES, which is capable of improving the financial return per capital cost by increasing the power storage capacity. Because the discharge temperature of current industrial compressors is lower than the maximum storage temperatures of the energy storage mediums in the world market [24,25], the storage potential of these TES mediums cannot be fully utilized in an AA-CAES system. If we can convert the reluctant wind power that is beyond the acceptable capacity of the electricity grid and the AA-CAES system, to thermal energy and also stores it in the TES units, then the power storage capacity of the system will be larger. This new system is called hybrid thermal-compressed air energy storage (HTCAES) system. It should be noted that this system is different from the TACAS system proposed by Active Power [26–28], which also uses electricity to heat TES. In principle, the TACAS system is adiabatic system, which dissipates the heat from air compression, while the HTCAES system is built on the basis of an adiabatic system and it recover the heat from air compression.

In the following sections, detailed operating procedures of the HTCAES system are presented and thermodynamic analyses are performed to quantitatively compare the overall performances of a HTCAES system and an AA-CAES system. The influences of the maximum TES storage temperature and the operating pressure on the performance of the HTCAES system are also investigated.

2. The hybrid thermal-compressed air energy storage

Fig. 1 is a schematic drawing that illustrates the operating steps of an AA-CAES system using solid thermal storage media. It consists of four main components: compressor, turbine, TES and cavern. During a charge process, ambient air is fed into the compressor, where the pressure and temperature of the air both increase. Then

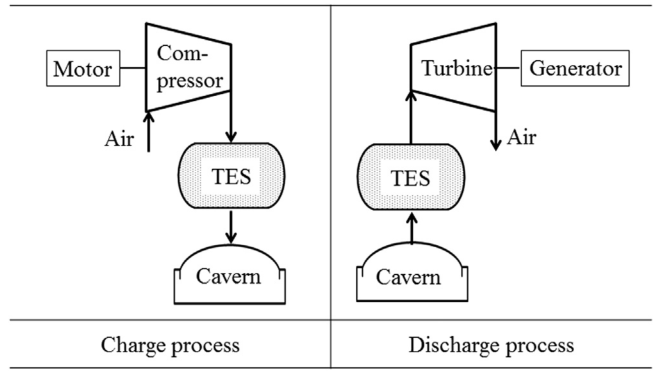

Fig. 1. Scheme of AA-CAES system.

the hot air is fed into the TES unit, where almost all the thermal energy of the air is absorbed by the TES. Afterward, the cooled compressed air is pumped into an underground cavern until the cavern pressure reaches the maximum operating pressure. During a discharge process, the compressed air flows through the TES, where thermal energy in the TES is returned to the compressed air. Then the hot compressed air is fed into the turbine to generate electrical power.

Fig. 2 shows the operating steps of a HTCAES system. The main difference between the HTCAES system and the AA-CAES system is that the charge process of the HTCAES system is divided into two steps: the first step is exactly the same as the charge process of the AA-CAES; the second step is using reluctant wind power to directly heat the energy storage media in the TES unit, increasing the storage temperature of the TES to a higher level. To achieve this, electric resistance heater should be deployed in the TES. And the maximum storage temperature of the media, which depends on the type of the media, should be higher than the compressor discharge temperature. Table 1 provides some sensible storage materials and their thermal properties and cost [24,25]. The discharge process of the HTCAES system is the same as that of the AA-CAES system.

Compared with the AA-CAES systems, the HTCAES system has following advantages:

(1) With the same scale of compressor, turbine, TES unit and cavern, the HTCAES system can generate more power using those abandoned wind power which cannot be utilized by the AA-CAES system, leading to increased competitiveness in economy. It should be noted that during most time of a year, the wind farms in China operate under 60%-load. Therefore, an AA-CAES system with an economically optimized capacity would always allow certain amount of abandoned wind power.
(2) The higher TES storage temperature could result in higher heat transfer efficiency for the TES unit, especially when radiation becomes important.
(3) With the same electricity demand, the volume of the carven can be reduced due to the larger capacity of the system. This means the geographic restriction of the system is lower.

Although these advantages make the HTCAES system attractive, the realization of such a system still involves some technical challenges which require further study. For example, the thermal expansion and contracting of the solid storage media is greater in the HTCAES system than that in the AA-CAES system, due to larger temperature variation. This needs to be considered in the design of the TES unit. Moreover, a properly thought-out plan is also required for the deployment of the electric resistance heater to increase heat