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Overview of research situation and progress on compressed air energy storage technology

Baohua Huang[1], Xiaozhi Qiu[1], Weimeng Wang[1], Hongzhi Li[2] and Weiqing Zhou[3]

[1]State Grid Jibei Electric Power Co. Ltd. Research Institute, North China Electric Power Research Institute Co. Ltd., Beijing 100045, China

[2]Beijing Bowang Huake Technology Co. Ltd., Beijing 100045, China

[3]Nanjing Institute of Technology School of Energy and Power Engineering, Nanjing 211167, China

wqzhou@njit.edu.cn

Abstract. So far, compressed air energy storage (CAES) system is another effective technology for large-scale energy storage which can improve grid flexibility and realize the grid generation of renewable energy. This paper reviews the developments of CAES technology including operation principles, application fields, technology performance of different types of CAES system and the current state-of-art. Finally, the potential key application prospects of CAES in future are discussed.

1. Introduction

With the rapid social economic development, electric power demand is continuously increasing. While it is difficult to maintain large-scale construction of traditional fossil power plant and the renewable energy power market must be developed vigorously. However, the inherent disadvantages of renewable energy power, such as uncertainty and intermittent will affect the stability of the grid and control of the power grid becomes more complicated.

The ability to migrate energy over time of energy storage system can provide effective solutions for the power grid connection problems of large-scale renewable energy generation. Simultaneously, the stable storage and output function of energy storage system can be used for power grid clipping and it is beneficial to improve power quality, also safety and stability of the power grid. Therefore, energy storage technology is extremely important for development of future energy systems and it becomes one of core issues in the field of energy research.

Currently, according to the medium, energy storage system can be divided into pumped energy storage, compressed air energy storage, flywheel energy storage and so on[1-3]. It also can be divided into physical energy storage, chemical energy storage and direct power storage technology [4-5]. Each energy storage technology has its own advantages and disadvantages. After comprehensively comparing the respective technical characteristics, currently there are only two energy storage technologies including pumped energy storage and compressed air energy storage which can be used in large-scale commercial applications.

Pumped energy storage power station is now widely recognized and applied because of its advantages including mature technology, large energy storage capacity, and high cycle efficiency. However the construction of pumped storage system needs rich water resources and suitable geography

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for construction of the upper and lower library [6], so it is severely constrained by geographical and geological conditions. As the pumped energy storage power station development continues, there are less and less suitable sites for construction of pumped energy storage system and it is difficult to continue to promote developing such systems on a large scale.

Compressed air energy storage (CAES) technology is another power storage system that enables large capacity and long-term energy storage. It converts excess electrical energy into pressure energy of compressed air through compressed air unit. When there is demand for electricity the compressed air stored in the gas tank is released which pushes the expander to work to produce electricity. Currently CAES technology is now receiving more and more attention as actual demand increases.

In this paper the research progress of CAES technology and its application are reviewed and forecasted. The content of the paper includes basic working principle, related application areas, types and characteristics of CAES system and development status all over the world. Finally, the application prospects of CAES technology is analyzed and several important directions for future development is proposed.

2. CAES technology

2.1 Working principle of CAES

The CAES system is developed on the basis of gas turbine technology. It uses the excess power energy to compress the air which is stored in a container. When during high power load hours the compressed air is released and pushes the expander to work power generation. In this way the transfer of energy in space and time is realized. The basic working principle of CAES is shown in Figure 1.

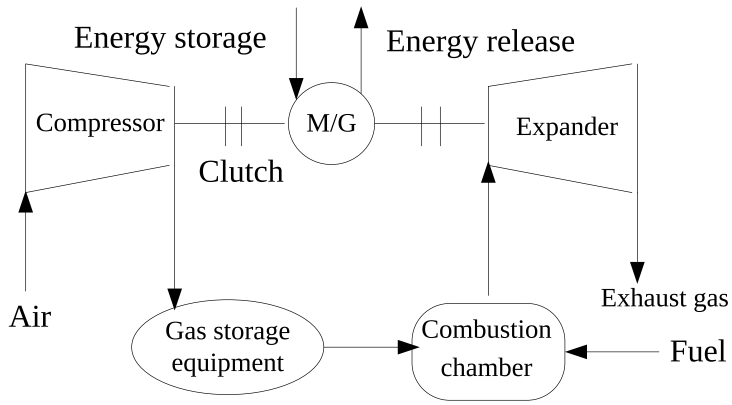

Figure 1. Working principle of CAES

As shown in Figure 1, CAES differs from conventional gas turbines technology in that the compressor and expander do not work at the same time. The compressor uses excess electric energy to compress and store the air in the gas storage device and the energy storage process is completed. In the process of release the compressed air enters the combustion chamber from the gas storage device and burns with the fuel and then pushes the expander to work power generation. Because the compressor does not consume the output power of the expander during the discharge process the CAES generally produces more than double the power of a gas turbine system [7].

Traditional CAES includes six major devices: ①The compressor is generally a multi-stage compression equipment with intermediate cooling; ②The expander is generally a multi-stage expansion device with intermediate reheat; ③Gas storage equipment generally chooses pressure vessels or large caves; ④Combustion chambers and heat exchange equipment are used for combustion and heat recovery; ⑤The generator is typically connected to the compressor and expander via a clutch; ⑥Control system and auxiliary equipment including control station, some pipeline valves and so on.

2.2 Main application areas of CAES

CAES technology was first applied to peak shaving and frequency modulation of electric power and as technology continues to evolve and update its application is more and more extensive including distributed energy, car power, renewable energy and so on.

1）Power system peaking and frequency modulation: Grid installed capacity must be built according to the maximum demand while the power plant unit has to be shut down or run at low load during low-load hours which will lead to waste of grid capacity. CAES can store excess energy during low load period and releases power energy during peak electricity usage period. In this way, the peaking and filling of the power system is realized and grid efficiency is also improved. In addition, CAES can also play the role of power system frequency modulation like other gas turbine power stations and hydropower stations.

2）Distributed energy system: Distributed energy system is the key technology to realize the future microgrid and the power supply reliability and stability of this system can be improved by using a compressed air system as the its load balancing device or backup power supply.

3）Renewable energy system: The power quality is poor generated by renewable energy sources such as wind and solar energy which results in serious light and wind abandon. The CAES stores intermittent, unstable and uncontrollable renewable energy which is transformed into electricity energy to meet demand. In this way large-scale grid connection of renewable energy can be realized and the energy abandon problem is solved.

4）Other applications include that CAES can also provide stable and reliable power supply for some special fields such as equipment manufacturing, medical facilities, defense facilities and so on.

2.3 Classification of CAES systems

Various types of CAES systems have emerged after years of development, in general there are three classifications [8]:

（1）By storage capacity, CAES system can be divided into large CAES system (100MW class), small CAES system (10MW class) and micro CAES system (10KW class).

Single unit power generation capacity of large CAES system is 100MW and it requires a higher capacity for air storage. Natural salt caves, mine caves and abandoned natural gas storage rooms can be chosen as gas storage device of CAES since they all have a large volume. Large CAES can be used to cut peaks and valleys in the grid, as well as to generate electricity from renewable sources.

Single unit power generation capacity of small CAES system is 10MW and high pressure container can be used as air storage device thus the system flexibility is improved. It is more suitable for energy supply in small areas such as distributed energy supply, small grid and so on. Also small CAES system can be combined with renewable energy to form a coupling system [9].

Single unit power generation capacity of micro CAES system is between several kilowatts and tens of kilowatts and less volume for air storage needed. Generally the micro CAES system is used as backup power in some specific fields such as military field, medical field and so on [10-11].

（2）According to the heat source, CAES can be divided into diabatic compressed air energy storage, adiabatic compressed air energy storage, and isothermal diabatic compressed air energy storage.

The working principle of diabatic compressed air energy storage (D-CAES) is that the high-temperature and high-pressure gas generated by combustion of mixture of the compressed air and fuel pushes the expander to work. The system structure is shown in Figure 2 which including cooling process during compression and reheating process during expansion in that the cycle efficiency is improved. This structure is used by Huntorf, the world’s first commercial application of CAES power station and its overall cycle efficiency is about 42% [12].

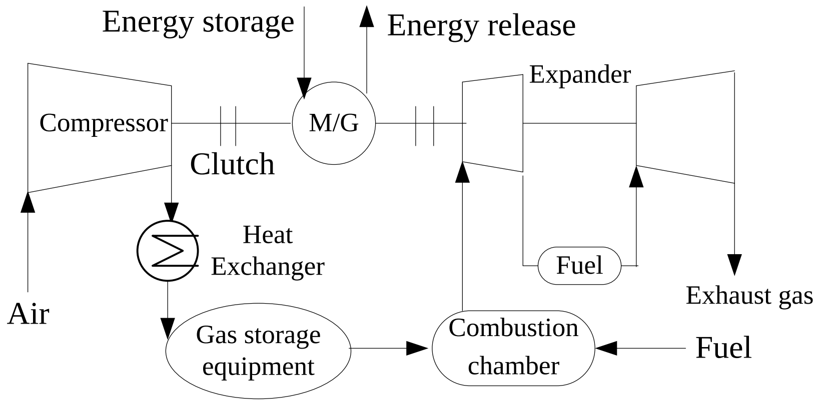

Figure 2. Structure of D-CAES

Since then, improvements have been made to such CAES systems. The CAES commercial power station McIntosh commissioned in US can increase cycle efficiency to approximately 54% through recovering the heat from the exhaust gas discharged from the expander which fuel consumption of power generation is roughly 1/4 less than that of Huntorf [13]. The system structure of McIntosh is shown in Figure 3.

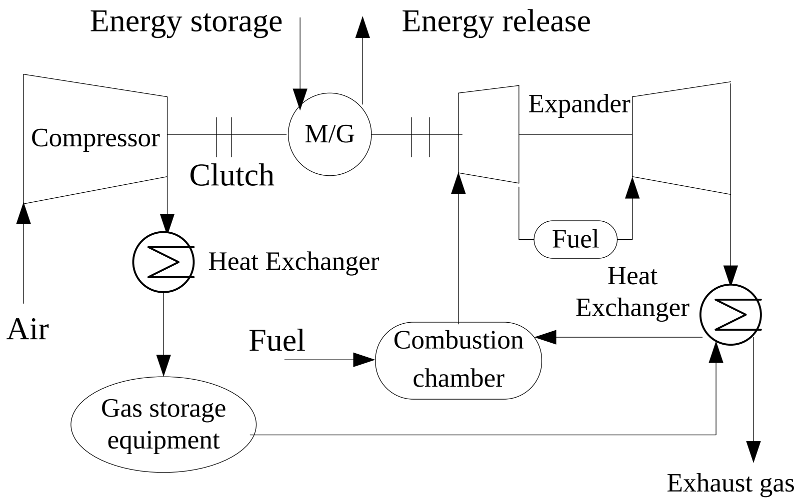

Figure 3. Structure of McIntosh

Adiabatic compressed air energy storage (A-CAES) saves heat generated during compression in heat storage device which can be used for increasing compressed air temperature in energy release stage. This system achieved the energy balance of the cyclic process and there is no need for external input fuel, the detailed structure of the system is shown in Figure 4. Because the important components of the system (such as heat exchangers, heat reservoirs, expanders, etc.) are usually working at high temperatures, it puts higher requirements on its design and operation and the corresponding cost also increases [14]. Among all the influencing factors, heat storage technology is the key technology of A-CAES and it is also a bottleneck that restricts system application.

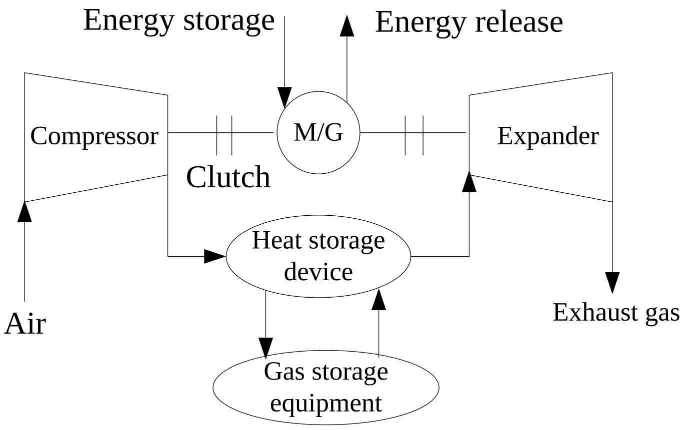

Figure 4. Structure of A-CAES

According to the theory of thermodynamics isothermal compression process consumes the least amount of compression work while isothermal expansion process produces the most amount of expansion work. The condition that achieves or approximates isothermal compression and expansion is that the energy storage system has good heat exchange capacity. Therefore isothermal diabatic compressed air energy storage uses a multi-stage compression cylinder and an expansion cylinder to enhance heat exchange in order to maintain isothermal property of system process.

（3）According to the coupling with other energy sources, currently the visible coupling methods include CAES-gas turbine coupling system, CAES-renewable energy coupling system, CAES-refrigeration cycle coupling system, CAES-internal combustion engine coupling system and so on.

Figure 5 shows a CAES-gas turbine hybrid system [7, 15] and its power generation process consists of two parts. On the one hand the compressed air exchanges heat with gas turbine exhaust and then enters the expander to do power generation. On the other hand, the hot air discharged from the expander continues to enter the combustion chamber of the gas turbine to enhance combustion and then the flue gas after combustion enters the turbine to generate electricity.

For the system shown in Figure 5 the functionality of compressed air is increased by recycling waste heat from gas turbines. At the same time, the hot air discharged from the expander can also serve as combustion air for the combustion chamber. The total energy output of this hybrid system can reach 3 times that of a single gas turbine and reducing fuel consumption by about 50% [14].

The intermittent and unstable characteristics of renewable energy such as wind and solar energy causes poor quality of the produced electricity and CAES can splicing these unstable energy sources for stable power output which provides a viable solution for grid connection of renewable energy [16-18].

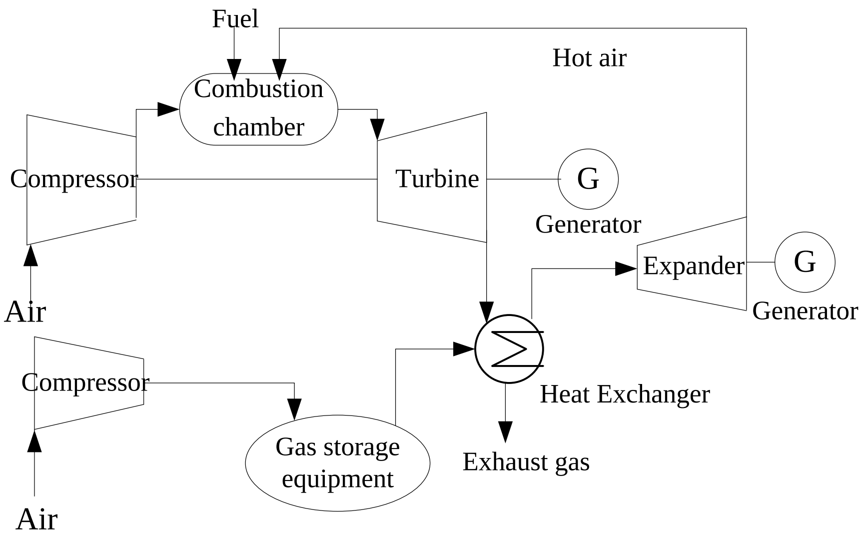

Figure 5. Structure of CAES-gas turbine hybrid system

In addition, the temperature of high pressure air in CAES system will greatly drop during the expansion process which can be used as a refrigerant to form CAES-refrigeration cycle coupling system. CAES can also be used in automotive power systems to form a CAES- internal combustion engine coupling system for improving the efficiency of automotive power systems [11].

3. Development status of CAES technology

3.1 CAES development abroad

The CAES concept was first proposed in Germany in 1949 and after 30 years of development the world's first commercial CAES power station Huntorf was built and put into operation in Germany and its basic structure is shown in Figure 2. The rated power of the compressor is 60MW while the power output of the expander is 290MW. The compressed air of Huntorf is stored in two salt caves 600 meters underground and the total volume is about $31\times10^4 m^3$. It takes about 6 minutes for the unit to reach full load and its charge-discharge time ratio is 4:1. The system efficiency of electric switching is about 20%. And the Huntorf power station was optimized in 2006 and the output power of the system is increased from 290MW to 321MW [1, 3].

The world's second commercial CAES power station, McIntosh was built in Alabama of USA in 1991 and its basic structure is shown in Figure 3. The compressor unit power of McIntosh is 50MW while the power output of the expander is 110MW. The compressed air of McIntosh is stored in a gas storage room 450 meters underground whose volume is $500000m^3$. It takes about 9 minutes for the unit to reach full load and its continuous power generation time is up to 26h. Different from Huntorf, McIntosh uses exhaust waste heat to heat high-pressure working fluid from the gas storage chamber to reduce fuel consumption by installing a heat recovery at the turbine exhaust. The system cycle efficiency is about 54% and electric switching efficiency can reach 25% [6].

Norton in Ohio in USA began planning to build a 2,700 MW large CAES power station in 2001, which is composed of 9 300MW units. The compressed air of this system is stored in a gas storage room 670 meters underground whose volume is $9570000m^3$ and its continuous power generation time is up to 2 days. The CAES power station in Iowa State is also under planning and it is used as part of the world's largest wind farm that allows wind farms to work properly even in windless conditions. The world's first megawatt isothermal compressed air energy storage system was built and started to work by US company SustainX in 2013. The system consists almost entirely of steel, water and has a service life of 20 years. The air temperature is almost constant throughout the whole process [8].

The power of CAES unit built in Japan in Sasakawa-cho in 2001 is 4MW and based on it 400MW CAES power station will be built. ABB Corporation of Swiss is developing a combined cycle CAES system and the overall cycle efficiency of this unit is theoretically higher than 70% [7]. A non-combustion advanced isothermal CAES system research called ADELE was launched by German Aerospace Center and German Zuplin Company and the technical difficulties of high temperature compressors and heat storage devices will be the key research problem. Currently, Russia, South Korea, Italy, etc. are also actively carrying out related technical research on CAES power stations.

3.2 CAES development domestic

In recent years, CAES technology has gradually attracted the attention of some domestic research institutions. The Institute of Engineering Thermophysics of the Chinese Academy of Sciences proposed supercritical CAES technology in 2009. The system uses heat and cold storage devices to achieve the recovery of compression heat and low temperature cold energy. The air in the energy storage process will be compressed to supercritical state and stored in a cryogenic storage tank by cooling and liquefaction that solves the problem of large volume of air storage.

State Grid Corporation established major science and technology projects in 2012 and Tsinghua University took the lead in conducting a non-combustion CAES technology with compression heat recycling. In 2014, the world's first 500KW non-combustion CAES simulation system (Tsinghua-IPC-CERRI-CAES, TICC-500) was built and power generation was successfully achieved. Experimental electric switching efficiency of TICC-500 reaches 40% which has the advantages of reliable technology, low cost and long service life [6].

State Grid Jibei Electric Power Co. Ltd. Research Institute built a 500kW×8h cryogenic liquefied air energy storage (LAES) power station in 2017[19]. The technical feature includes recovering cold energy generated by expansion process and air liquefaction. The system has high energy storage density and flexibility and its basic structure is shown in Figure 6. On this basis, 10MW supercritical CAES power station is also in plan.

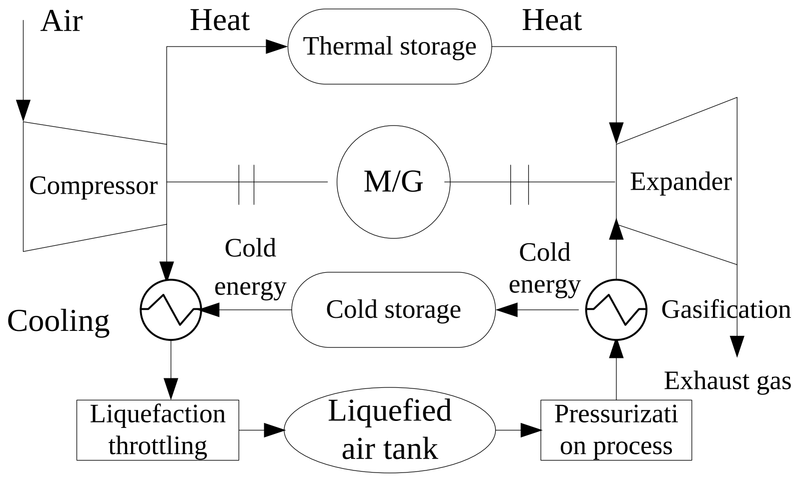

Figure 6. Structure of LAES

4. Application Prospect of CAES

In spite of the advantages of CAES affirmed by researchers within the field, there are a few important deficiencies in CAES being pointed out by researchers [20] which greatly limit the application and promotion of CAES. However, CAES technology is still a very effective solution for achieving large-scale energy storage in the future and its application prospects concentrates in several important directions. (1) Coupling power generation system with other renewable energy sources for improving system flexibility. (2) Small CAES system is simple in structure and flexible in function and has high return on investment since it is easy to overcome difficulties in the technical process. (3) Coupling with distributed energy system cold, heat and electricity supply can be achieved and energy efficiency is also increased.

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