

Application Trend Analysis of Compressed Air Energy Storage and Gas Storage

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Abstract: Large-scale energy storage technology is the key to improve the utilization of renewable energy, reducing energy pressure and achieving sustainable development. Among all energy storage technologies, the most promising physical energy storage technique is thought to be compressed air energy storage, featuring qualities including scalability, affordability, durability, and environmental friendliness. Nowadays, with the quick advancement of compressed air energy storage technology, air storage device research has gotten a lot of attention. The material properties of gas storage systems primarily determine their features, and this paper accordingly classifies and summarizes the gas storage devices in this technology, discussing the applications and characteristics of above-ground gas storage devices, natural underground caves and artificial caves. On this basis, it compares various gas storage devices, describes the challenges encountered in the development of gas storage devices, and introduces the development status of compressed air energy storage and gas storage. Finally, it looks ahead to this trend in the hope of achieving sustainable growth.

Keywords: Compressed Air Energy Storage, Application Scenario, Gas Storage Device.

1. Introduction

Nowadays, in order to reduce pollution emissions and protect the ecological environment, governments around the world have begun to encourage the application of new energy. Due to the volatility and randomness of power systems using wind, solar, and other new energy sources, there are a lot of energy abandonment in actual operation, which makes the utilization rate of new energy at a low level for a long time. Among the new energy storage, the electrochemical energy storage facilities have not yet formed a recognized security solution. There are potential safety hazards such as fire and explosion. Pumped storage is limited by geographical factors seriously. Compressed air energy storage (hereafter abbreviated as CAES), in comparison, is safer and offers the benefits of a high energy storage scale, a long duration before discharge, long usage time, and full utilization of both hot and cold electricity. It involves the conversion and storage of various energy forms of cold, heat and electricity, which is more convenient for coupling various thermal systems [1]. It improves the flexibility of working mode and the efficiency. Therefore, large-scale development of CAES technology is an inevitable method to achieve safe and efficient use of new energy.

Using compressed air as a medium to store surplus electric energy, CAES is a new technology, which was proposed by German engineer Stal Laval in 1949 [2]. Its basic principle is: when the power consumption is low, the power consumption drives the compressor to compress air and store it. During the peak of power consumption, the compressed air expands and enters the turbine for work to generate electricity [3]. This technology is equivalent to a large battery, which can be used to adjust power peak and valley and improve power quality. As air expansion needs to absorb heat to do work, traditional compressed air energy storage needs to burn natural gas to supplement heat during power generation to improve power, it leads to carbon emissions and environmental pollution problems of traditional CAES technology. To minimize the waste of energy and environmental pollution, this technology is also constantly being improved and upgraded.

The Huntorf power plant (Germany, 1978) and the McIntosh power plant (the United States, 1991) are the only two large-scale commercial compressed air storage power stations in existence at the

moment. Additionally, numerous nations place a high value on this technology, planning and constructing numerous CAES pilot projects.

Gas storage device is an important part of CAES technology. For micro and small plants, the compressed air storage equipment generally adopts the above-ground gas storage device, mainly made of metal or composite materials. For large-scale CAES plants (above 100 MW), the gas storage equipment is generally underground gas storage, which is mainly divided into natural caves and artificial caverns [4].

This paper will introduce various gas storage devices used in CAES technology, analyze the benefits and drawbacks from the perspectives of construction technology difficulty, economic cost performance, site selection difficulty, safety, and suitable scale, sort out the key technology focus and difficulties of CAES, and finally analyze the technology development trend and study the future path.

2. Classification of gas storage

2.1. Aboveground gas storage device

2.1.1 Metal material gas storage

According to the storage pressure, metal pressure vessels can be classified into low pressure gas storage devices ($0.1 \text{ MPa} \leq P < 1.6 \text{ MPa}$), medium pressure gas storage devices ($1.6 \text{ MPa} \leq P < 10 \text{ MPa}$), high pressure gas storage devices ($10 \text{ MPa} \leq P < 100 \text{ MPa}$) and ultra-high pressure gas storage devices ($P \geq 100 \text{ MPa}$). Compressed air energy storage usually uses the high pressure level. The metal high-pressure gas storage device has good sealing performance, high operation reliability, mature design and manufacturing technology, and flexible installation and layout. Cylindrical tanks and spherical tanks are common metal gas storage devices. The stress of spherical tank is more reasonable under the same internal pressure. However, the material and process requirements for spherical tanks are higher. On the whole, the high-pressure gas storage tank required for CAES has certain technical requirements and high cost.

2.1.2 Combined material gas storage

The reinforced thermoplastic composite gas storage pipeline is made of high-strength aramid fiber, glass fiber, basalt fiber, steel wire, etc. The inner and outer layers are corrosion-resistant and abrasion resistant polyolefins. The pressure bearing range is 7~25 MPa. In addition, compared with metal materials, it can reduce weight by about 30%. It is corrosion resistant, fatigue resistant, and has safe failure mode. The energy consumption for production of the same volume is only 1/3~1/4 of that of metal materials, which is more consistent with the development trend of sustainable development today. Compared with metal pipes, reinforced thermoplastic composite pipes can save more than 25% of material and processing costs. They can withstand high pressure while maintaining a certain degree of flexibility, which can be made into coils to further reduce transportation and installation costs. It seems likely to use composite pipes to replace metal pressure pipes for gas storage.

On the other hand, scientists are also trying the underwater constant pressure gas storage scheme. In this case, the gas storage device's lower internal and exterior pressure differential greatly lowers the pressure bearing capability of the pressure vessel needs. The flexible composite material air container with arbitrary folding deformation is used to test the underwater compressed air energy storage system. Thin Red Line Aerospace, a Canadian company, manufactured a small pumpkin shaped flexible air receiver, and carried out indoor tank experiments and 25 m deep real underwater experiments respectively [5]. Hydrostor Corporation of Canada used the water drop shaped air container as the air storage device to conduct compressed air energy storage tests at 80 m underwater [6]. The flexible composite airbag is usually made of coated fabric, which has the advantages of good sealing and corrosion resistance. The widely used coated fabrics include polyvinyl chloride lining coated fabric and polyurethane (TPU) lining coated fabric. However, this kind of material has high technical requirements and is still in the test stage.

2.2. Natural underground cavern gas storage

The natural underground caverns are large in scale and low in construction cost, and have been widely used in the field of CAES, mainly including natural salt caves, underground aquifers, hard-rock caverns and abandoned mine caverns.

2.2.1 Salt cave gas storage

Salt cave gas storage is the best choice of underground high-pressure gas storage globally because of its remarkable advantages. It has low permeability and good creep behavior, good sealing performance, stable mechanical properties, and can adapt to the alternate transformation of storage pressure during operation. Generally speaking, as long as the salt cave is drilled into the underground salt layer, the cave for gas storage can be formed by water injection to melt the salt, so the cost of salt cave gas storage technology is low. Salt cave reservoirs are mostly based on the old cavities that have been mined. The main cost is the initial reconstruction and later maintenance, which is relatively smaller compared with the construction investment cost. Both Huntorf Power Station and McIntosh Power Station use deep buried natural salt caves as gas storage devices, with gas storage scales of 310000 m³ and 560000 m³ respectively, and gas storage pressures of 10 MPa and 7.5 MPa [7]. However, the operation experience of Huntorf Power Station shows that the air stored in the salt cavern gas storage has a high salt content and is highly corrosive to compressed air pipelines and units [8]. Therefore, particular focus should be given to the corrosion prevention of pipelines and units in the project construction. In addition, the distribution range of salt rock strata suitable for reservoir construction is limited, and the geographical conditions limit the development of CAES power plants in salt cave gas storage. While service life lengthens, such gas storage may have problems such as salt cave creep, deformation and failure of salt rock interlayer. Large buried depth of some salt caverns, too long gas transmission pipeline or too small diameter may lead to large air pressure loss, thus affecting the efficiency of the power station [9].

2.2.2 Aquifer gas storage

The aquifer underground gas storage stores the compressed air in the pore medium of the aquifer. Compressed air is stored in porous formation with strong permeability, and the groundwater is discharged to form huge bubbles. Due to the movement of the air groundwater interface, the gas storage pressure is relatively constant, which is conducive to the operation of compressor and expander. Compared with other large-scale energy storage technologies, using aquifer pore media as gas storage space has advantages in economy [10]. The biggest disadvantage of aquifer gas storage is that the investigation of an aquifer appropriate for gas storage is challenging due to the inadequate controllability and predictability of the gas storage. The system's scale for injection and production is also constrained by the limited permeability of the aquifer. When the permeability is large, it is simple to lose pressure and air, which shortens the system's time under sustained operation. However, the underground aquifer gas storage also has the defect of difficult location, and the gas cushion layer consumption is large. At present, the underground aquifer as the gas storage device has not been commercialized. There are only some research projects, including the 25 MW porous rock layer compressed air storage system in Sesta, Italy, and the IMAU project in the United States, which uses porous sandstone structure to store gas [11].

2.2.3 Hard-rock gas storage

The fact that there are numerous varieties of hard rock suitable for the construction of the reservoir and the strata are widely spread is the main benefit of the freshly excavated hard rock cavern gas storage. There are often a variety of hard rock strata that are suitable for the construction of the reservoir in places where there is a demand for its construction. Therefore, the location of the gas storage hard-rock cavern is quite straightforward. Compared with other types of gas storage, the biggest disadvantage of hard-rock cavern gas storage is that its construction cost is relatively high. The hard rock has higher compressive strength, and also has greater construction difficulty. It also needs to set a special sealing structure layer to prevent high-pressure gas leakage. Shallow burial and

expanding the power station's working pressure range can lower the cost of construction, which will boost the economic indicators for the one-time investment in underground cavern gas storage. The hard-rock gas storage has the least layout restriction, the highest unit cost and relatively few operation problems. With the large-scale development of CAES projects, different support and sealing forms can be adopted according to the characteristics of different strata and rock masses, and the construction cost of underground projects has some room for reduction. Norton CAES project in Ohio, USA, uses abandoned limestone mine located 670 m deep underground to store compressed air, with a capacity of 9,570,000 m³ and a storage pressure of 11 MPa [11].

2.2.4 Abandoned mine gas storage

A lot of mining space have been formed in the mining process of various metal and non-metallic mines, and a large number of mines have been abandoned due to the depletion of resources. These abandoned mines and roadways have potential as underground gas storage after transformation [12]. The investment cost can be reduced by using abandoned mines to build underground gas storages of compressed air storage power plants. However, the gas storage is required to withstand high pressure and frequent pressure changes during operation, and only a few mines meet the basic conditions. There are many problems in the utilization of abandoned coal mines and roadways that need to be studied in depth, such as insufficient stability, roadway collapse and ground subsidence; The difficulty of groundwater treatment and groundwater pollution caused by large burial depth; There may be problems in the disposal of harmful gases such as coal mine gas. For large-scale abandoned metal ores, the rock mass quality of the associated rock strata is relatively good, the compressive strength is high, the stability of roadways and shafts is high, and the technical difficulties of transformation and related environmental problems are relatively small. Therefore, it is more suitable for transformation into an underground gas storage of a CAES power station.

Briefly, the natural underground caves are large in scale, low in cost, and have obvious advantages. However, due to the special geological and geographical conditions, it is difficult to achieve flexible layout and large-scale promotion. In addition, they are deeply buried underground, with complex geological structures, difficult to monitor gas leakage, and difficult to effectively guarantee the structural stability, and there are also certain potential safety hazards.

2.3. Artificial cavern gas storage

Artificial caverns weaken the dependence on special geological and geographical conditions, mainly including shallow underground artificial lining cavern gas storage devices and underwater concrete artificial gas storage chambers. The artificially lined cavern is lined with concrete, combined with the sealing layer and surrounding rock. Among them, the load generated by high-pressure gas storage is mainly borne by the surrounding rock. The sealing layer and concrete lining ensure good sealing, which is better than the natural cave sealing, and can make the gas storage pressure higher. An air tightness test in Japan shows that the maximum leakage rate per day is less than 0.5% under the gas storage pressure of 0.9 MPa [13]. Sweden has built an artificial rock cave 115m below the rock layer with reinforced concrete as the lining, with a volume of about 40000 m³. The gas storage pressure can reach 20 MPa [14]. South Korea has studied the feasibility and system design of rock lined caverns. The pilot project of its CAES power station began in 2011. A tunnel shaped cavern with a diameter of 5m and a length of about 200m has been built in the limestone with a depth of 100m underground. Concrete is used as the lining and 300 mm steel plates are used to strengthen the sealing [15]. To verify the feasibility of shallow buried underground gas storage, China has built a shallow buried hard rock test reservoir in a granite layer in Changsha, Hunan Province, with a buried depth of about 110 m and a clearance volume of about 28.8 m³. Many complete compressed air charging and discharging cycle tests were carried out with the design pressure of 10 MPa, and the results showed that the sealing performance was good under the condition of long-term high-pressure gas storage [16].

The concrete artificial air storage chamber, which can be used in underwater environment, has also been tried as the air storage device of underwater CAES system. The gas storage device is an open

structure, allowing free access of seawater. When compressed air is used for energy storage, high-pressure air is used to discharge seawater from the gas storage device. When venting, seawater enters the gas storage device under the action of hydrostatic pressure to maintain a constant air source pressure. Seymour et al. of the University of California, San Diego proposed to use a concrete box with a 300-meter length, an 8-meter height, and a 30-meter breadth as the gas storage device. The concrete chamber of is used as the air storage device [17]. However, the underwater concrete artificial air chamber causes more water content in the compressed air, which is easy to cause corrosion damage to the working equipment. At present, it has not been applied in engineering.

3. Development status

Compressed air energy storage and gas storage includes metal material gas storage, combined material gas storage, salt cave, aquifer gas storage, hard-rock gas storage, abandoned mine and artificial cavern gas storage and other forms. According to the statistical analysis of all planned, under construction and completed projects, the unit capacity of salt cavern gas storage is large, and the investment per kilowatt is relatively low; The abandoned and old mines and newly built caves can also be used for the construction of large power plants, and the investment per kilowatt is slightly higher than that for the construction of salt caverns; The above ground gas storage devices are generally used in small and medium-sized power plants, and most of them are in the test stage. At this stage, the average investment per kilowatt is generally higher than that of underground gas storage. Because large CAES power stations need large gas storage space, and the above ground gas storage devices are expensive, the projects under construction and already in operation at this stage mostly use underground gas storage, namely salt caves, new hard-rock caverns and mine cavern reconstruction.

It was anticipated that the Iowa Stored Energy Park project would be operational by 2015. The aim was to construct a 270MW CAES plant with 75MW to 100MW wind capacity. The project had to be abandoned in 2011 since the investors determined that the permeable sandstone aquifers in Iowa are unsuitable for CAES [18].

In China, where saline rock is widely distributed, large-scale CAES projects in recent years basically use salt caves as gas storage. For example, Jintan Salt Cavern Compressed Air Energy Storage National Experimental Demonstration Project, the first non-supplementary combustion compressed air energy storage plant will be officially put into commercial operation in May 2022 [19].

4. Conclusion

At present, the scale and complexity of the power grid are increasing day by day. Power generation and power dispatching have had difficulties as a result of the power grid's peak and valley, and the risk of large-scale blackouts in the power grid is gradually increasing. Therefore, energy storage technology with large capacity and high efficiency is needed to relieve the peak power supply pressure of the grid, and provide emergency backup, so as to make sure the grid is operating safely and profitably. The two commercial CAES plants have been built for peak shaving and valley filling.

The benefits and drawbacks of various types of underground gas storage for CAES are compared and analyzed. For countries and regions with corresponding rock strata distribution, salt rock and hard rock caverns are the preferred types of gas storage for building large-scale compressed air energy storage power stations at this stage.

Natural underground cavern gas storage is large in scale and low in cost, but it depends on the geological and geographical conditions. Thus, it is necessary to actively research and develop new gas storage forms such as artificial caverns, metal materials and composite materials to get rid of the dependence of CAES system on geographical conditions and promote its large-scale popularization and application. For the new type of gas storage, it is urgent to further carry out research work on

accurate thermodynamic model, underground cave stability evaluation and composite material gas storage structure characteristics to offer theoretical direction for the choice and application of gas storage devices in the CAES system.

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