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Research on Storage Capacity of Compressed Air Pumped Hydro Energy Storage Equipment*

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ABSTRACT

Compressed air pumped hydro energy storage equipment combines compressed air energy storage technology and pumped storage technology. The water is pumped to a vessel to compress air for energy storage, and the compressed air expanses pushing water to drive the hydro turbine for power generation. The novel storage equipment saves natural gas resources, reduces carbon emission, and improves the controllability and reliability. The principle of compressed air pumped hydro energy storage is introduced and its mathematical model is built. The storage and generation process of the novel equipment is analyzed using the model. The calculation formula of the storage power is deduced in theory in different situations of isothermal and adiabatic compression. The optimal storage scheme is given when the capacity and withstand pressure of the vessel is definitive, and the max available capacity and the equipment utilization efficiency evaluation of the scheme is given.

Keywords: Power Storage; Compressed Air Energy Storage; Hydraulic Equipment; Optimal Operation; Isothermal Process; Adiabatic Process; Equipment Utilization Efficiency

1. Introduction

In recent years, as the problems of resources shortage and environment pollution become serious, the new energy generation increases rapidly, especially the wind power[1]. However, compared with the traditional generation, the wind power generation is characteristic of intermittence, volatility and randomness. The large scale integration of wind power will aggravate the unbalance of the supply and the demand of power grid, and the peak regulation ability of power grid is a serious obstacle to the development of the wind power[2]. Energy storage technology will provide a very effective way to solve these problems.

In various energy storage technologies, the practical large scale storage only includes pumped storage and compressed air energy storage. The pumped station requires high geographical conditions, the long construction period, the large initial investment and damages to the ecological environment. Compressed air energy storage (CAES) technology is a very promising energy storage system and attracts great attentions in the world, as it does not require strict geographical conditions and is economic[3].

Traditional CAES power station is divided into energy storage subsystem and power generation subsystem[4]. The energy storage subsystem, comprised of compressor, motor and gas chambers, converts the low-cost electrical energy to the compressed air stored in gas chambers such as caves and abandoned mines. During the peak load period, the power generation subsystem, comprised of the gas turbine, combustion chamber as well as the heater, generates power energy by the gas turbine driven by the compressed gas combustion[5].

Compare with other energy storage technologies, advantages of compressed air energy storage system include[6]:

(1) It is suitable for the construction of large power plants (>100MW). Its storage capacity is just less than the pumped storage power station. CAES has long working time, and it can continue working for a few hours or even a few days.

(2) The unit construction costs and operating costs of large-scale CAES stations are lower than the pumped storage power station. CAES has good economic efficiency.

(3) CAES has a long lifespan, and it can store/release energy tens of thousands of times. Its efficiency can reach about 70%, which is close to the pumped storage power station.

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However, every storage technology has shortcomings [7,8]. The disadvantages of compressed air energy storage system include:

(1) Traditional compressed air energy storage system must work with gas turbine power station, which consumes a lot of natural gas when generation. The traditional scheme consumes a large amount of non- renewable energy and releases a large amount of CO_2, mismatching the development requirements of reducing carbon emission and preventing of global warming[9,10].

(2) Compressed air energy storage systems require conditions of high temperature and high pressure. It needs high requirements and high maintenance costs. In addition, the failure rate of the turbine is high and its service life is short.

2. Compressed Air Pumped Hydro Energy Storage

The compressed air storage technology combined hydro equipment attracts great attentions of technicians. The essence is that the energy is stored in the compressed air, and is extracted by the hydro turbines driven by high pressure. Therefore the equipment can be called compressed air pumped hydro energy storage equipment. Many delightful progresses in this area appear in recent years.

An implementation of compressed air pumped hydro energy storage is put forward in [11]. Its block diagram is shown in **Figure 1**. The system includes an air compressor, a reservoir, a tank of gas-water and a pump/turbine-motor/generator. Before the first storage process, air is compressed into the tank of gas-water by the compressor, reaching a preset pressure in the tank. Since then the compressor would not work anymore. During valley demand periods, water in the reservoir is pumped to the tank by the water pump. With the increase of the water level, water squeezes gas in the tank, and the gas is compressed. The result is the increase of the pressure. During peak demand periods, the high-pressure water promotes the hydraulic turbine to generate power.

A similar compressed air pumped hydro energy storage system is proposed in [12]. Its block diagram is shown in **Figure 2**. It is different from the previous energy storage system in a tank of high-pressure gas, which stores only compressed air. The tank of high-pressure gas is connected with gas compressor and gas turbine generator. Before storage, compressor compresses air to the tank of high-pressure gas. The tank of high-pressure gas supplies preset pressure for the tank of gas-water. During the peak load, the high-pressure gas in the tank of gas-water push the water, driving the hydraulic turbine to generate power. During the valley load, the motor-pump pumps the water in the reservoir to the tank of gas-water using the surplus power of the grid. The gas pressure increases in the tank of gas-water, and the pressured gas is stored in the tank of high-pressure gas at last. During the peak load, the gas turbine generator can be used to generate power as a supplement. When the air pressure is insufficient, the gas compressor will work again.

Compared with the traditional CAES system, the two compressed air pumped hydro energy storage systems don't consume natural gas, and don't need the air turbo-expander, nor the gas turbine or auxiliary heating systems, solving the two problems of traditional CAES systems mentioned above. In addition, generating by the hydro turbine improves the controllability of the system and the reliability of the equipment operation, and simplifies the energy storage system. The novel system combines pumped storage and compressed air energy storage technology by the tank of gas-water which is buried in the rock layer deep underground. It can be used widely in areas short of water and heating fuel.

3. The Principle Analysis of Compressed Air Pumped Hydro Energy Storage

The mentioned two compressed air pumped hydro energy storage systems above can be described by the following model.

The vessel is shown in **Figure 3**. Its volume is V_1, and the initial pressure of inner air is an atmospheric pressure (shown in **Figure 4(a)**). Before storage, compressed air of certain pressure is preset by the gas compressor. P_1 is the preset pressure (shown in **Figure 4(b)**). During valley load period, external water is pumped into the vessel consuming the surplus power of the grid. With the increase of the amount of water, the inner air is compressed and the pressure increases. The power energy is converted to the potential energy of the compressed air. The

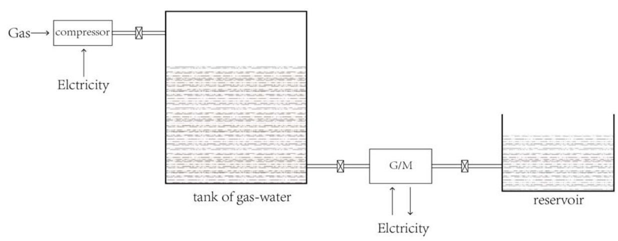

Figure 1. The block diagram of an implementation proposed in [11].

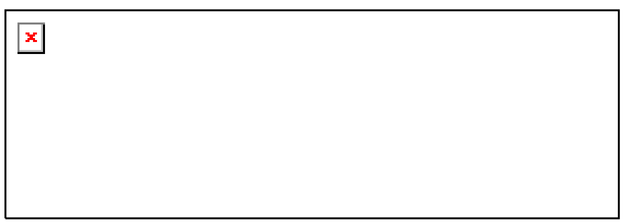

Figure 2. The block diagram of an implementation proposed in [12].

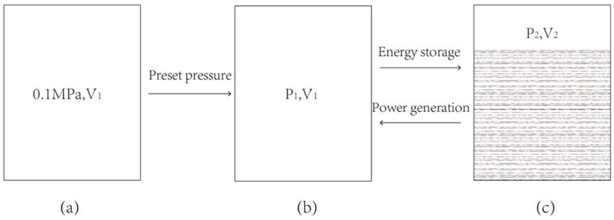

Figure 3 . The model of compressed air pumped hydro energy storage.

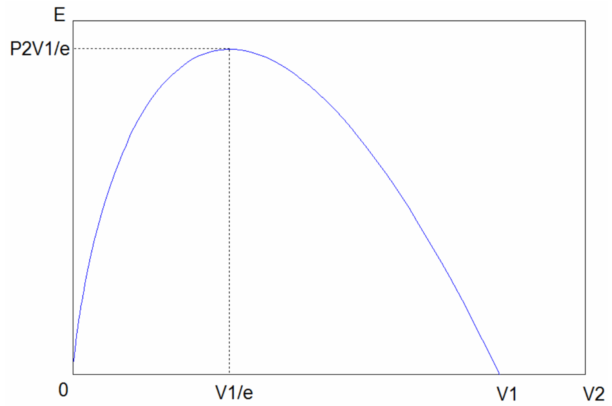

Figure 4. The relationship between E and V_2 in isothermal process.

max pressure of the compressed air is P_2, which is the withstand pressure value of the vessel, and the volume of the air is V_2 at the moment (shown in **Figure 4(c)**). When generation, the high pressure water is pushed out, driving the hydro turbine to generate electrical power energy. When all the water from the vessel is discharged, all the energy which can be emitted is released.

Obviously, in order to store the most energy in the storage system, the air in the vessel should be compressed to the withstand pressure value of the vessel P_2. Besides, the amount of energy is related to the volume of the compressed air V_2. By setting the volume ratio of the gas and water reasonably, the largest amount of energy can be stored, maximizing the utilization of storage devices. Because compression and expansion are isothermal or adiabatic process, the following formula of the relationship between the volume of the compressed air V_2 and the energy E is deduced individually in two different situations. And then get the volume of air when the energy maximizes.

3.1. Isothermal Process

In the process of power generation, the volume of the air in the vessel is V_x, and the pressure is P_x. In the isothermal process, the relationship between the volume and the pressure is as following:

$$P_2 \cdot V_2 = P_x \cdot V_x \tag{1}$$

The process of power generation is over after all the water in the vessel is discharged. The converted energy in this process is:

$$E = \int_{V_2}^{V_1} P_x dV_x = \int_{V_2}^{V_1} \frac{P_2 V_2}{V_x} dV_x = P_2 V_2 \ln V_x \mid_{V_2}^{V_1} = P_2 V_2 ln \frac{V_1}{V_2} \tag{2}$$

For a given vessel, its capacity V_1 and withstand pressure value P_2 are fixed values. Form the formula (2), the amount of released energy is just determined by the volume of the compressed air when pressure maximizes. The preset pressure is $P_1 = P_2 \cdot V_2 / V_1$. Thus, the other conclusion is that the amount of released energy is just determined by the preset pressure.

Get the derivative to V_2 from (2), and the equation is as follows:

$$\frac{dE}{dV_2} = P_2 ln \frac{V_1}{V_2} - P_2 \tag{3}$$

When the derivative equals 0, the volume of compressed air is $V_2 = V_1 / e$. At the moment, the preset pressure is $P_1 = P_2 / e$, and the energy is $E = P_2 \cdot V_1 / e$. The relationship curve between E and V_2 is shown in **Figure 4**.

It can be concluded, in the isothermal process, in order to release the most energy from a vessel whose volume is V_1 and withstand pressure value is P_2, the initial pressure should be preset to $P_1 = P_2 / e$. When the air is compressed to the max pressure P_2, the volume of the air is $V_2 = V_1 / e$. The max energy which can be released in the process of power generation is $E = P_2 \cdot V_1 / e$.

3.2. Adiabatic Process

In the adiabatic process, the relationship between the volume and the pressure is as following:

$$P_2 \cdot V_2^{\gamma} = P_x \cdot V_x^{\gamma} \tag{4}$$

where γ is the heat capacity ratio of the air. The heat capacity ratio of the atmosphere is 1.4. And then, the converted energy in this process can be computed:

$$E = \int_{V_2}^{V_1} P_x dV_x = \int_{V_2}^{V_1} \frac{P_2 V_2^{\gamma}}{V_x^{\gamma}} dV_x = \frac{P_2 V_2^{\gamma}}{1-\gamma} V_x^{1-\gamma} \mid_{V_2}^{V_1}$$

$$= \frac{P_2 V_2^{\gamma}}{1-\gamma} (V_1^{1-\gamma} - V_2^{1-\gamma}) \tag{5}$$

Get the derivative to V_2 from (5), and the equation is as follows:

$$\frac{dE}{dV_2} = \frac{P_2}{1-\gamma} [\gamma (\frac{V_2}{V_1})^{\gamma} - 1] \tag{6}$$

When the derivative equals 0, the volume of compressed air is $V_2 = V_1 / \sqrt[\gamma-1]{\gamma}$. At the moment, the preset pressure is $P_1 = P_2/\gamma^{\gamma/\gamma-1}$, and the energy is $E = P_2 \cdot V_1/\gamma^{\gamma/\gamma-1}$. The relationship curve between E and V_2 is shown in **Figure 5**.

It can be concluded, in the adiabatic process, in order to release the most energy from a vessel whose volume is V_1 and withstand pressure value is P_2, the initial pressure should be preset to $P_1 = P_2/\gamma^{\gamma/\gamma-1}$. When the air is compressed to the max pressure P_2, the volume of the air is $V_2 = V_1/\sqrt[\gamma-1]{\gamma}$. The max energy which can be released in the process of power generation is $E = P_2 \cdot V_1/\gamma^{\gamma/\gamma-1}$. In the process of adiabatic compression, the temperature increase of the gas can be computed using the following equation:

$$T_2 \cdot V_2^{\gamma-1} = T_x \cdot V_x^{\gamma-1} \quad (7)$$

3.3. Example Calculation

Assume the volume of vessel V_1 is 10m^3, and the withstand pressure value P_2 is 10MPa. By (2)(3)(5)(6), the max extracted energy E and preset pressure P_1 can be calculated in isothermal and adiabatic processes.

In compressed air pumped hydro energy storage systems, the preset pressure of the vessel needs to consume power energy to supply, which cannot be extracted by the hydro turbine. The consumed power needed to preset pressure is E_0. In single storage-generation process, the ratio of extracted energy to the total stored energy is:

$$\eta = \frac{E}{E + E_0} \times 100\% \quad (8)$$

Assume the preset gas is compressed into the vessel in an isothermal way. By the formula (2), the consumed energy E_0 can be calculated, and then the ratio η can be calculated.

Assume the initial temperature of preset air in the vessel is $t_0 = 0$℃. The temperature rise in the adiabatic compression can be calculated by the formula (7).

The results in isothermal and adiabatic processes are shown in **Table 1**.

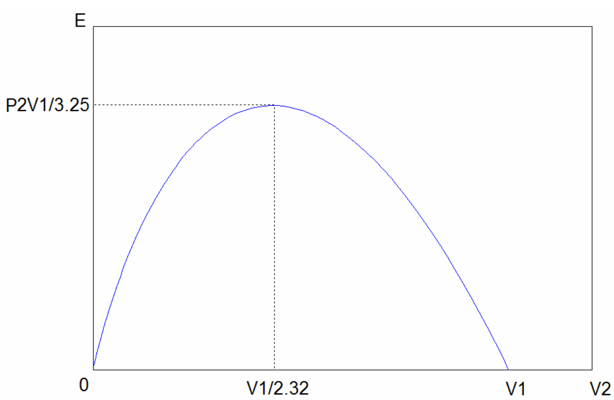

Figure 5. The relationship between E and V_2 in adiabatic process.

Table 1. The results in isothermal and adiabatic processes.

Index	Isothermal process	Adiabatic process
P0(MPa)	3.68	3.08
E(×10^6 J)	36.8	30.77
E0(×10^6 J)	132.68	105.57
η	21.7	22.57
t0(℃)	0	0
t(℃)	0	109.27

As can be seen from the above data, in the adiabatic process, the gas pressure will be affected by the temperature of the gas, which will promote the increase of the gas pressure when the air is compressed. Thus the stored energy in the adiabatic process is less than that in the isothermal process. The compressed air pumped hydro energy storage systems mentioned above have no adiabatic treatment, nor isothermal measures. So the practical systems will work at a state between the adiabatic and isothermal results. When the extracted energy reaches maximum, the preset pressure will be a value between 3.08 MPa and 3.68 Mpa, and the max power energy released will be a value between 30.77 × 10^6 J and 36.8 × 10^6 J, and the ratio η will be a value between 21.7% and 22.57%. Based on these data, we can draw the following conclusions. Compared with traditional CAES systems, the compressed air pumped hydro energy storage systems store less "effective" energy, that is, the energy which can be released when peak load period. Considering the construction costs in the engineering projects accounted for a large proportion, for the same equipment, the unit electricity cost in the compressed air pumped hydro energy storage systems is higher than the traditional systems.

4. Conclusions

Compressed air pumped hydro energy storage has good prospects for development. The generation unit is constructed by hydraulic equipment, breaking through the shackles of traditional mechanical power generation by turbines and avoiding the problems of excessive increase of carbon emissions. The principle of compressed air pumped hydro energy storage is analyzed. The calculation formula of the storage power is deduced in theory in different situations of isothermal and adiabatic compression. The relationship curve between the storage power and the initial state is obtained. The optimal storage scheme is given when the capacity and withstand pressure of the vessel is definitive, and the max available capacity and the equipment utilization efficiency evaluation of the scheme is given.

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