Design and Feasibility Analysis of Compressed Air Aquifer Energy Storage System

Mingyu Zhu
School of Power Engineering, North China Electric Power University, Baoding, Hebei 071000, China

Abstract. Compressed air energy storage system is developing rapidly as the most promising energy storage technology, and gas storage device is one of the main components of compressed air energy storage system. Aquifer compressed air energy storage can break the dependence of traditional compressed air energy storage on geological conditions such as large rock caves, and can realize large scale storage of compressed air. In this paper, the development and progress of compressed air energy storage in aquifer are summarized firstly. Then, taking 3.5 Mw energy storage scale as an example, the energy storage model of underground aquifer with buried depth of 800m in horizontal stratum is established by using numerical simulation method. The formation of the initial airbag after gas injection and the cycle times of the pressure system during the system cycle are analyzed. The experimental results show that after a complete cycle, the pressure change in the formation is small; as the cycle continues, the effective gas phase volume in the formation for the energy storage release cycle is slowly reduced. The aquifer has wide distribution and good sealing. It is feasible to store compressed air as a gas storage. The corresponding system design should be carried out according to the actual geological conditions.

Keywords: Compressed air energy storage; aquifer; energy storage characteristics; numerical simulation.

1. Introduction
As the proportion of renewable energy in the energy structure is increasing, how to carry out large-scale storage of electrical energy becomes the key to breaking the bottleneck between renewable energy and grid connection. So far, the world's energy storage technologies that can be applied to 100 MW and above are only pumped energy storage and compressed air energy storage. Pumped storage has higher energy storage and conversion efficiency, but due to the high requirements on terrain and water source, the application of this technology has great limitations. Large-scale compressed air energy storage systems often require special geological conditions to build large gas storages, such as rock caves, salt caves, abandoned mines, etc., which also greatly limits the application range of compressed air energy storage.

Groundwater aquifers are widely used in geological storage of carbon dioxide and underground storage of natural gas, confirming that aquifers can effectively store gases, and aquifers are widely
distributed. Some preliminary studies and experiments abroad have also shown that aquifers can be used as compressed air energy storage. "Gas storage", if the underground aquifer is used as the "gas storage", it can greatly reduce the geological conditions of compressed air storage, and then get rid of the dependence of traditional compressed air energy storage on large caves. This paper selects the underground aquifer as the gas storage for compressed air energy storage, and mainly designs the compressed air energy storage system for the underground part. The underground system mainly includes the formation of the initial airbag and the cycle of energy storage and energy release. The numerical simulation method is used to analyze the initial airbag formation and the pressure and gas phase saturation during the system energy storage and release cycle, and verify the aquifer as the reservoir. The feasibility of the gas storage for compressed air storage.

2. Research status and progress
Compressed air energy storage is the second large-scale electric energy storage technology after pumping energy storage. The concept was put forward as early as 1949. The study of aquifer compressed air energy storage is relatively late. In 1980, the US Department of Energy launched an extensive compressed air energy storage research program in the United States to verify the use of aquifers for compressed air storage by conducting aquifer injection and extraction air tests in Pittsfield. The test results confirm that air is injected into the aquifer to form a large airbag, and the air can be extracted at a certain rate for power generation. In recent years, the Iowa Municipal Utilities Association has proposed a compressed air energy storage project that works directly with a wind farm in Iowa. Its air storage medium selects the underground aquifer, which is the first to date. The project uses a pore aquifer to store air, and the project is in a suspended state due to factors such as energy storage scale and economy.

3. Compressed air underground aquifer energy storage system design
The compressed air aquifer energy storage underground system mainly includes two stages: initial airbag formation and subsequent energy storage and energy release cycle. Before starting the cycle, a large amount of buffer gas needs to be injected to form the initial air bag to provide faster pressure support for the pumping process and prevent the liquid water from being extracted to affect the system power generation. Referring to the existing mature natural gas storage project, different geological structures have an important influence on the formation of the initial airbag. Theoretically, the anticline is more conducive to gas sequestration in the geological structure. For the actual site selection, the horizontal aquifer is selected as the gas storage. The library will greatly expand the application range of compressed air aquifer energy storage. Therefore, in this paper, the horizontal aquifer is used as the gas storage system for system design. After the initial balloon formation, a system energy storage release cycle is performed. In the storage of compressed air aquifers, the system cycle can be designed as a daily cycle or a weekly cycle. The daily cycle is studied as an example, and the energy storage scale is set to 3.5 MW. During a single cycle, the gas injection and energy release phases of the energy storage phase are the same. Referring to the operating time period of the Huntorf power station, in the energy storage stage, such as solar energy and wind power generation, the designed energy storage period is 12 h, the gas injection rate is 3 kg·S⁻¹, and the energy generation during the peak period of electricity consumption is 3 h, and the pumping rate is 8 kg·S⁻¹, the intermediate system is in the shutdown phase.

4. Model establishment and analysis

4.1. Numerical simulation
Establish an idealized basic model and select a study area with a plane radius of 2 km in the aquifer and divide it. The injected gas layer is located in the middle of the model, with a thickness of 50 m. The main stratigraphic parameters are shown in Table 1. The initial conditions are calculated according to the gravity balance, the geothermal gradient is assumed to be 30 °C·km, the boundary conditions are the first type of boundary conditions, and the compressed air parameters are as follows.
Figure 1. Model domain and mesh discretization

4.2. Pressure distribution

Figure 2 shows the pressure change with time at the injection point (r = 0.5 m) and the position of two different monitoring points during the initial balloon formation. It can be clearly seen that near the injection point, the pressure increases sharply after the instantaneous injection, and then the pressure tends to be stable as the gas injection is gradually stabilized. The pressure at the monitoring point 1 (r=23.0 m) is relatively flat. At the remote monitoring point 2 (r=142.7 m), the pressure gradually increases with the gas injection, and the growth rate slows down.
A complete energy storage release cycle includes four stages: gas injection, energy injection, pumping, pumping, and stopping. In the process of energy storage and energy release, three cycles of 1590 to 1670 were selected as an example to analyze the pressure change process at the injection point and at two monitoring points. Injecting energy storage at state point 1 and reaching state point 2 for 3 h, the pressure gradually increases; state point 2 to state point 3 is the 4.5 h phase of stoppage, compressed air drives the groundwater to move around, and the pressure gradually decreases; in the release phase of state point 3 to state point 4, with continuous pumping, the pressure drops rapidly, and the speed is about 0.8 MPa·h; then enters the formation recovery stage, corresponding to the state point 4 to the state point 5 in the figure. At this time, the surrounding formation pressure is higher than the injection point pressure, and the groundwater displacement compressed air moves toward the vicinity of the wellbore, the pressure gradually recovered.

4.3. Cycle number analysis

The number of times the gas in the initial bladder is allowed to circulate continuously is called the number of system cycles. As the circulation continues, the gas in the initial balloon migrates around, and the gas at the edge of the balloon gradually dissolves in the water, and the effective gas is reduced. When the cycle is reduced to the point where the cycle cannot be satisfied, the cycle ends and the energy continues to be lost along with the cycle. The system can cycle 110d in the basic model. In order to make the system sustainable, two methods are designed to supplement the effective gas in the aquifer: one solution is to inject another balloon when the effective gas is insufficient in the formation; the other method is to inject more during the daily gas injection process. Inject a certain amount of gas to maintain a sustainable system cycle.

The two schemes were simulated and analyzed. In the gas injection supplement scheme of the daily cycle, different gas injection rates were designed, as shown in Fig. 4, from 2 kg/s to 6 kg/s. It can be found that the number of cycles of the system for a single initial airbag increases logarithmically with the increase of the gas injection rate. When the temperature is increased to a certain extent, the number of cycles of the system decreases. This is because during the cycle, the excess supplemental gas causes a large pressure difference between the injection point and the surrounding pressure, and the energy loss is large, so that the available gas in the formation does not increase after it reaches saturation.
Figure 4. System cycle time variation with daily make-up injection under the same initial gas bubble

Another method is to replenish the same amount of compressed air as the initial airbag after the cycle is stopped. The simulation results are shown in FIG. It can be seen from the figure that the initial airbag can be used for the maximum number of cycles, and the number of times the supplementary airbag can be used for circulation is not much different. The reason that the initial airbag is larger than the number of cycles of the supplementary airbag system is because the gas phase is formed during the initial balloon formation. The halo radius is small and the gas loss is less. When the supplementary airbag is injected, the gas unit time loss in the formation is stable. As shown in Fig. 9, under the same cycle number, the bottom hole gas saturation of the supplementary airbag is lower than the initial airbag. The bottom hole saturation

Figure 5. System cycle time variation with make-up gas bubble formation

Figure 6. Gas saturation variation under different make-up gas bubble conditions

5. Conclusion

This paper summarizes the development and progress of aquifer compressed air energy storage, and uses the underground aquifer as the gas storage to design the compressed air energy storage system. The numerical simulation method is used to analyze the pressure and system cycle times during the energy storage and energy release process. In the basic model, the initial airbag can be used for system circulation 111d. By using another airbag injection when the effective gas is insufficient in the formation, and injecting a certain amount of gas during the daily circulation gas injection, the continuation of the system cycle time is realized.

At present, the research and design of the compressed air storage energy of the aquifer is still in the basic stage, and there is no substantial progress. There is still a large amount of basis for the future aquifer compressed air energy storage. The problem needs to be explored, including the study of the effects of different parameters on the scale and efficiency of the system's energy storage.
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