Compressed Air Energy Storage System

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Abstract

Large-scale power storage equipment for leveling the unstable output of renewable energy has been expected to spread in order to reduce CO_2 emissions. The compressed air energy storage system described in this paper is suitable for storing large amounts of energy for extended periods of time. Particularly, in North America, China and other areas, where rock salt layers are widely distributed, using underground spaces formed in the rock salt layers to store compressed air can reduce the unit kWh cost of equipment. The equipment's responsiveness was obtained on the basis of the data for large-scale demonstration equipment of 1 MW class, verifying that the equipment can respond to commands within seconds. This paper further describes the future development of the compressed air energy storage system.

Introduction

Recently, the introduction of renewable energy is progressing rapidly worldwide as a result of the requirements imposed both by the Paris Agreement on climate change control to reduce greenhouse gas emissions and also by the significant decrease in the unit power price of photovoltaic and wind-power generation.

There is, however, the problem that the power generated by photovoltaic and wind-power generation, or renewable energy, is not stable, due to solar irradiation and weather conditions. Therefore, if it is interconnected to the grid as-is, it becomes a disturbance factor to the power grid. This may disrupt the balance between the supply and demand of electricity, causing frequency fluctuations, and in the worst case, triggering power outage. Renewable energies such as wind power and photovoltaic power cannot be controlled to match the demand, causing a mismatch between the supply and demand. This mismatch is now relaxed mainly by adjusting the output of thermal power generation. If the unstable output can be leveled to decrease the adjustment load, the utilization of renewable energy will be encouraged. Hence, the wide-spread use of large-scale power storage plants that can level the power generation output is required, from the viewpoint of CO_2 emission reduction.

It is against this backdrop that Kobe Steel has received an order for, and delivered, a new compressed-air energy storage (hereinafter referred to as "CAES") system using a screw-type compressor/expander from the Institute of Applied Energy and has contributed to a verification test conducted by said institute and Waseda University for a year and a half beginning in April 2017. It should be noted that this verification test was carried out as a part of the "R&D Project on Grid Integration of Variable Renewable Energy" promoted by the New Energy and Industrial Technology Development Organization (hereinafter referred to as "NEDO").

This paper introduces the performance of the CAES plant designed and built by Kobe Steel and describes the future development in Kobe Steel.

1. CAES plant

Kobe Steel's CAES technology comprises storing compressed air in a tank with a screw-type compressor first; and subsequently expanding the stored compressed air with a screw-type expander to drive a power generator that is directly connected to the expander and thus to generate electricity, wherein the heat generated by the compression is collected by a heat medium for preheating the compressed air before it flows into the expander, thereby improving charge/discharge efficiency. In addition, thermal insulation measures are taken to prevent the charge/discharge efficiency from decreasing due to heat dissipation loss in the equipment.

Fig. 1 and **Fig. 2** show the flow of the CAES system at the time of charging and discharging, respectively. As can be seen by comparing these, the directions of the flows of the compressed air and heat medium are opposite, but the main components are almost the same for charging and discharging. A screw compressor can be used as-is for a screw expander by rotating its screw in the reverse direction. This means that the system can be configured as a compressor-cum-expander. Such a configuration not only makes the plant compact, but also reduce its cost significantly.[1)]

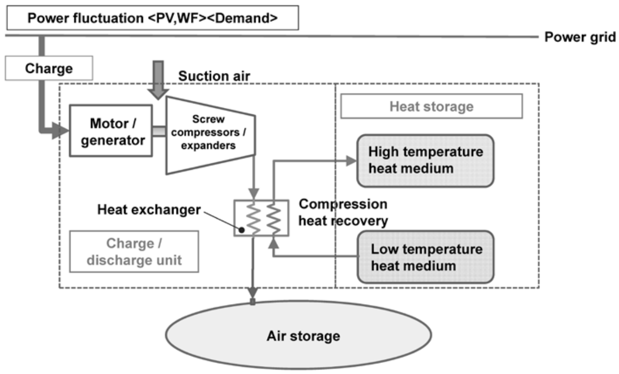

Fig. 1 Charge flow of CAES system

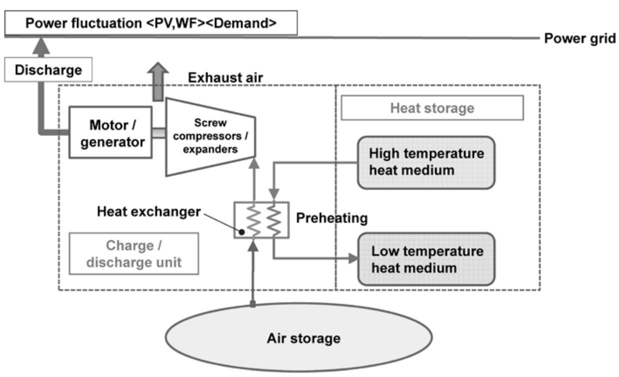

Fig. 2 Discharge flow of CAES system

2. Overview of demonstration plant

When developing the technology for a thermal insulation type CAES, Kobe Steel first installed a 50 kW class small-scale prototype in the Kobe Corporate Research Laboratories and conducted various basic tests. The know-how gained from this small-scale prototype has led to the delivery of a large-scale demonstration plant of 1 MW class to the Institute of Applied Energy. The following provides an overview of these two plants.

2.1 50 kW small-scale prototype

Fig. 3 shows the appearance of the 50 kW class small-scale prototype installed in Kobe Corporate Research Laboratories of Kobe Steel. This plant is based on Kobe Steel's standard oil-free screw compressors (output 55 kW) that have been modified into a compressor and expander for experiments on CAES technology. The accumulator that stores compressed air consists of four steel tanks, each having an internal volume of 7.6 m^3 and a withstanding pressure of 0.97 MPa G.

In February 2016, this in-house experimental plant began power generation tests, including the test runs of the compressor and expander and the performance test of the heat exchanger. The

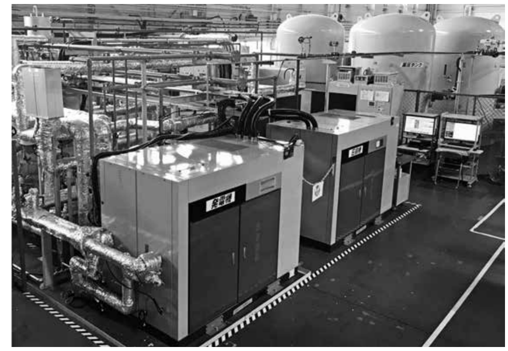

Fig. 3 Appearance of 50 kW small-scale prototype

Fig. 4 Appearance of 1 MW large-scale demonstration plant

knowledge gained through these tests has led to the design and construction of a large 1 MW class demonstration plant.

2.2 Large-scale demonstration plant of 1 MW

Fig. 4 shows a large-scale demonstration plant of 1 MW class, that was installed at Higashiizu-cho, Kamo-gun, Shizuoka Prefecture (hereinafter referred to as the "Izu demonstration plant").[2), 3)] This plant was installed adjacent to the Higashiizu Wind Farm of Tokyo Electric Power Company Holdings, Inc., and underwent a pre-use inspection by the Ministry of Economy, Trade and Industry in March 2017 before beginning operation in April of the same year. Since then, the Institute of Applied Energy and Waseda University had conducted various experiments on the fluctuation relaxation of power generated by the wind farm for a year and a half until the power plant was closed in October 2018.

This plant comprises two sets of 500 kW basic units, each consisting of three units, namely, a charging unit, heat-accumulation unit, and discharging unit, in which the two sets are connected in parallel, enabling the charging/discharging of 1 MW power at the maximum.

The housing of each unit had the size of a 20-foot container to facilitate transportation from the Kobe Steel factory to the verification test site and on-site installation work, etc. As a result, the installation work period, including the installation of the

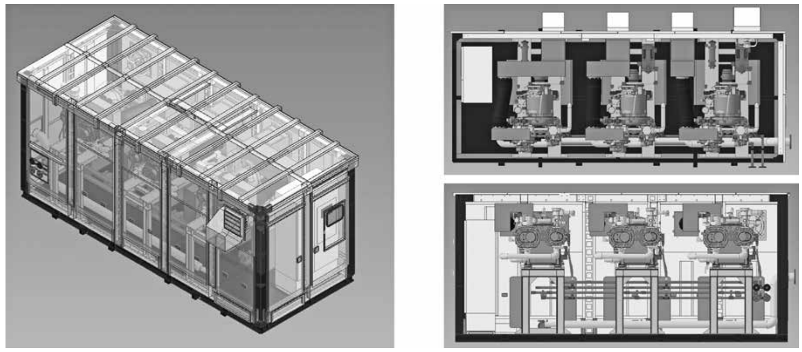

Fig. 5 500 kW charging unit

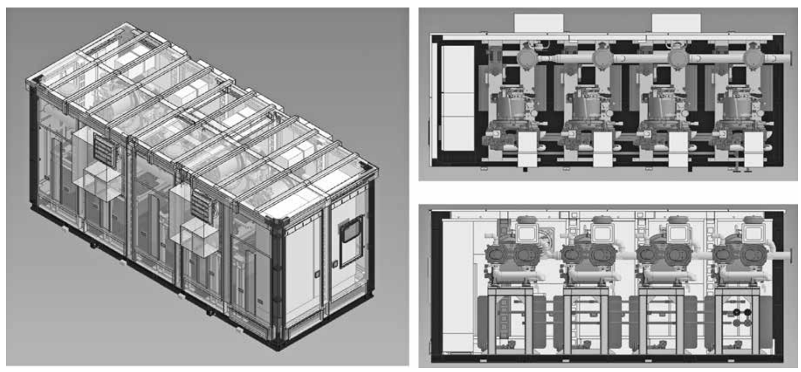

Fig. 6 500 kW discharging unit

compressed air tank, was reduced to less than one month. Housing in a standard container also offered the advantage of facilitating maintenance work after the beginning of operation. In addition, multiple basic units were connected in parallel in order to avoid stopping the entire plant during periodic inspections and repairs. **Fig. 5** and **Fig. 6** show the overviews of the charging unit and discharging unit, respectively. Each figure includes a transparent perspective view showing the internal structure, along with the front view and top view.

The charging unit houses three main bodies of Kobe Steel's standard oil-free two-stage screw compressors of 160 kW class with heat exchangers placed underneath. The combination of unit control and revolution control has enabled a continuous output control up to 500 KW. The heat generated during compression is absorbed in the heat medium by the heat exchanger and stored in the heat medium tank housed in the heat-accumulation unit. The maximum temperature of the heat medium was kept below 200℃, so as to allow the use of the general-purpose compressors.

The discharging unit, on the other hand, houses the main bodies of four 160 kW class oil-free two-stage screw compressors, which are rotated in the direction reversed from that during compression so as to serve as expanders. The difference in the number of compressors and that of expanders is resulted from the consideration of the charge/discharge efficiency. The high temperature heat medium in the heat-accumulation unit is used as the heat source of the heat exchanger for heating the compressed air at the ambient temperature in the air tank to produce high-temperature compressed air. The high-temperature compressed air is supplied to the expander so that the screw is rotated with the torque caused by the pressure difference from the atmosphere to drive the power generator.

3. Performance of Izu demonstration plant

The Izu demonstration plant used screw-type compressors and expanders. This offered the advantage of excellent responsiveness to charging and discharging commands compared with the turbo-type compressors and expanders used in conventional CAES systems. This section focuses on the responsiveness obtained by operating the Izu demonstration plant.

3.1 Startup performance

Fig. 7 shows an example of the response characteristics when the Izu demonstration plant is started from the standby state to the maximum charging state of 1 MW. Also, **Fig. 8** shows an example of the response characteristics when it

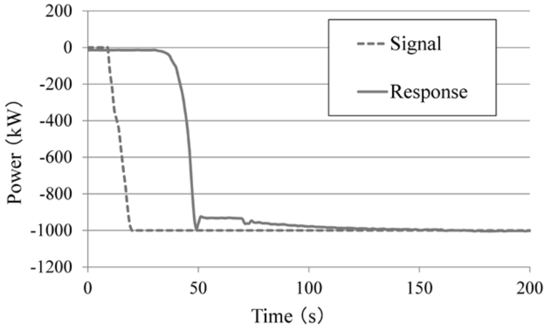

Fig. 7 Response time in charging

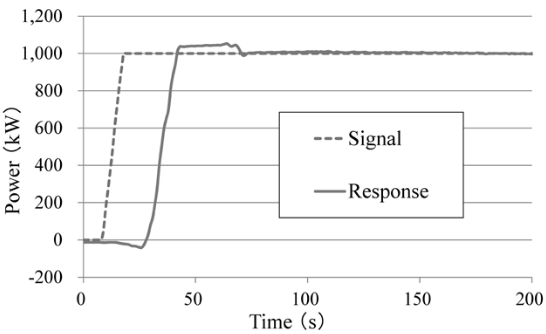

Fig. 8 Response time in discharging

is launched to the maximum discharging state of 1 MW. In Fig. 7 and Fig. 8, zero on the vertical axis indicates the zero charging/discharging state, negative values indicate charging states (compressor operating states), and positive values indicate discharging states (expander operating state).

As shown in Fig. 7 and Fig. 8, the maximum charging or discharging power can be reached in approximately 30 seconds from the stopped state after receiving the command value (signal). This indicates that it is fully usable for relaxing the output fluctuation of the wind farm.

The response time of start-up is expected to remain almost the same for even larger-scale plants of several tens of MW class, since they can be handled by adding the units in parallel. A backup power supply in case of power outage requires a separate device for measures against momentary power failure, and the plant is exploitable as equipment that can supply a large amount of electric power fairly soon.

3.2 Command-following performance

The power generation output of a wind farm changes greatly depending on the wind conditions, and thus the responsiveness to the output command is important in order to mitigate the fluctuation.

The evaluation of the command-following performance of the Izu demonstration plant used the simulated command (Reg. D) for the response

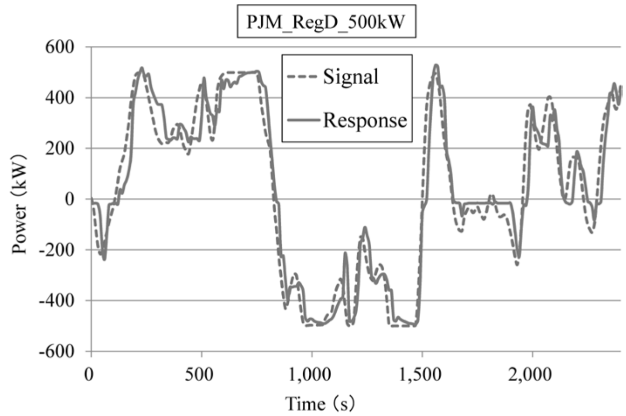

Fig. 9 Response to PJM Reg. D signal

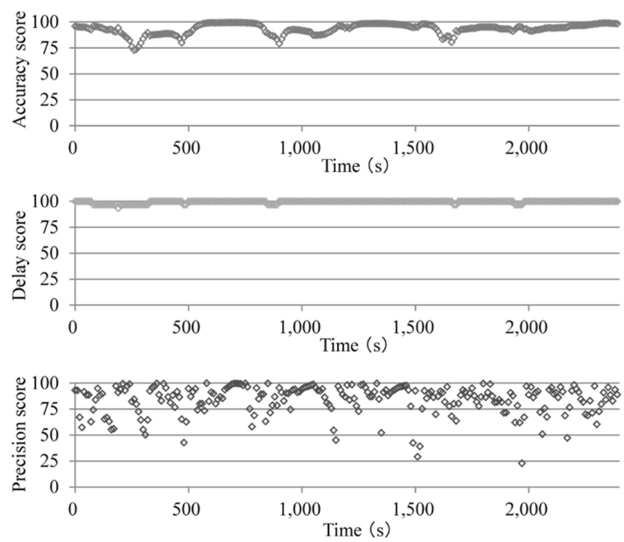

Fig.10 Results of PJM performance scores

confirmation test released by PJM Interconnection LLC (PJM), a power transmission company in the northeastern United States,[4] and the responsiveness of the CAES plant was evaluated. **Fig. 9** shows an example of the results.

The power command in Fig. 9 uses a waveform obtained by scaling the Reg. D Normalized Self-Test Signal released by PJM with the maximum value of plus or minus 500 KW. The response characteristics of the CAES plant were measured on the basis of the PJM responsiveness performance evaluation method. The evaluation results are shown in **Fig.10**. The evaluation is based on three scores, i.e., accuracy score, delay score, and precision score. The evaluation equation for each score is shown below.

$$Accuracy\ Score_{\delta=0\ to\ 5\ min}=\gamma_{Signal\ ,Response(\delta,\delta+5min)}$$

$$Delay\ Score=Abs\left|\frac{\delta\text{-}5\ Minutes}{5\ Minutes}\right|$$

$$Error=Avg\ of\ Abs\left|\frac{Response\text{-}Regulation\ Signal}{Hourly\ Average\ Regulation\ Signal}\right|$$

$$Precision\ Score=1-\frac{1}{n}\sum Abs(Error)$$

wherein, γ : correlation coefficient,
n : number of samples per unit time.

For the Izu demonstration plant, the simple average of each score of the 40-minute test was accuracy, 93.3; delay, 99.46; and precision, 84.12, respectively, with the average of the three values recording a high score of 92.29. PJM requires a performance score of 75 points or higher for a continuous test signal of 40 minutes as a condition for entry into the frequency adjustment market. The above score for the Izu demonstration plant is considered to be at a level that can sufficiently be used for a power-coordinating facility in the electricity market. It should be noted that several tests, performed by changing the conditions such as the amount of compressed air storage and the scaling width of the Reg. D test waveform, has confirmed a performance meeting the requirement of 75 points or above.

4. Future perspective

4.1 Performance improvement and cost reduction

The Izu demonstration plant has shown that a plant using oil-free screw compressors as key components can be used for the relaxation of output fluctuations of a wind farm. In order to expand the use of CAES facilities, however, further performance improvement and cost reduction are necessary.

Currently, Kobe Steel is aiming at achieving both the performance improvement and cost reduction by combining the charging unit and discharging unit. The company is also considering increasing the storage pressure to reduce the volume of the compressed air storage tank.

Fig.11 shows the overview of a charging-cum-discharging unit in which the screw compressor currently under consideration is used for charging and discharging and the maximum storage pressure is increased to 2 MPaG. This unit comprises three screw compressors with a maximum discharge pressure of 1 MPaG and one screw compressor with a maximum discharge pressure of 2 MPaG, each being usable as a compressor-cum-expander. The combination of unit control and revolution control has enabled continuous output control up to 555 KW.

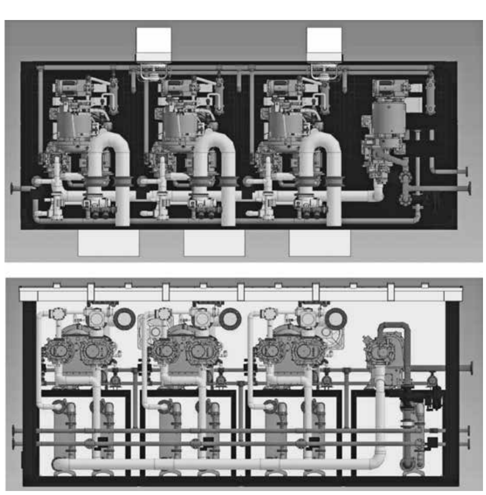

Fig.11 555 kW charging-cum-discharging unit

A study is being conducted to boost the pressure to approximately 5 MPaG by combining screw compressors with a discharge pressures higher than those of the example shown in Fig.11.

4.2 Global developments

There are specific plans to introduce CAES plants in countries where the introduction of renewable energy is progressing, particularly in North America and the People's Republic of China. In China, the construction of a CAES plant of several tens of MW has begun in Jiangsu as a national project.

The reason why CAES plants are highly evaluated in these countries is the existence of underground rock-salt beds, which do not exist in Japan. In North America, for example, underground rock-salt beds are widely distributed in plains on the eastern side of the Rocky Mountains, from Texas to Alberta, Canada, passing through Kansas, and on the eastern side of the Great Lakes. These underground rock-salt beds are not only used for rock salt mining, but also utilized as an underground space, formed in the rock-salt beds, for storing natural gas, for example. Since these underground spaces are excellent in airtightness, they may be used as storage tanks for compressed air; they represent/there is a possibility of realizing storage for large amount of energy at a low cost. For example, the power storage duration of a general large-scale lithium-ion battery with greater than MW capacity is from 4 hours to 8 hours at the longest. In a CAES plant that can secure a giant underground space such as a rock salt cavern, the power storage time can be significantly extended from approximately 24 hours to 48 hours.

The plains on the eastern side of the Rocky Mountains mentioned earlier are roughly in line with the suitable location for wind farms in the United States. Hence, there are expectations in this region for controlling the electrical power generated by the wind farms and planning the generation of power based on wind-power. Furthermore, there are expectations of obtaining backup power sources that will cover the needs of communities of a certain size during power outages.

Fig.12 depicts the concept of a CAES plant that utilizes the underground space formed in a rock-salt bed as a storage tank for compressed air. Fig.12 shows an example in which the CAES plant is interconnected with the transmission line of a wind farm, but it can also be interconnected with a photovoltaic power generation plant.

The only apparatuses installed on the ground are the containers housing the charging/discharging units and the electric plants. Although the footprint area may be no major issue in North America, the plants on the ground can be compactly organized with an appearance similar to that of a lithium-ion battery.

In 2019, Kobe Steel's proposal, "Demonstration Study of Underground Compressed Air Storage for Realizing Large-Scale Power Storage (North America)" was adopted by NEDO as a part of the "International Demonstration Project on Japan's Energy Efficiency Technologies: surveys of the suitability of demonstration requirements." In response to this, the company is currently exploring the possibility of developing CAES plants, mainly in the North American region.

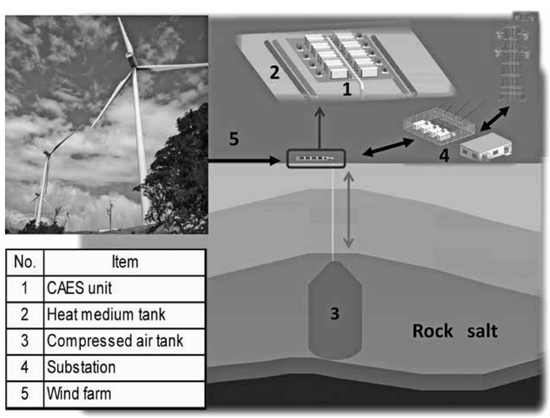

Fig.12 CAES plant using rock salt cavern

Conclusions

As a large-scale power storage unit with specifications for long-term storage and extended continuation of discharge, the compressed-air energy storage plant can be superior to (less expensive than) other power storage units in terms of the ratio of plant cost to the amount of power (kWh) that can be stored, that is, the unit price of kWh. In particular, when an underground space such as a rock salt cavern is utilized as a compressed air storage tank, it may be possible to configure a power storage plant providing power at several thousand yen/kWh, which is less expensive than the power provided by chemical secondary batteries, such as lithium-ion batteries.[5)]

Rock-salt beds are widespread in North America, China, and Central and Eastern Europe. Therefore, Kobe Steel believes that the spread of compressed-air energy storage plants can contribute to the promotion and introduction of renewable energy in these regions.

Finally, we would like to express our gratitude to the Institute of Applied Energy and Waseda University, which adopted Kobe Steel's compressed-air energy storage plant as a demonstration apparatus and gave Kobe Steel a great deal of guidance and advice in connection with the verification test at Izu.

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