Compressed Air Energy Storage Experimental Platform with off-grid Operation

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Abstract: The compressed air energy storage (CAES) experimental platform can play a role in research and training. Due to the large changes in experimental working conditions and many sudden abnormal situations, it is easy to disturb the safe operation of the power grid when it is integrated into the power grid. By constructing a three-layer compressed air energy storage experimental platform, equipped with a complete test and operation monitoring system, using multiple sets of high-power light bulbs as loads, the experimental platform can be operated off-grid. It has the advantages of simple structure, low cost, wide adaptable voltage range, easy observation of experimental results, etc., and has broad application value.

1. Introduction

With the rapid development of the power industry, large-scale new energy sources are integrated into the grid on the basis of traditional energy sources, and the intermittent and volatility of new energy power generation require a large amount of energy storage to stabilize and ensure the consumption of new energy\cite{1}. Compressed air energy storage has the characteristics of large capacity, low pollution, and long life. It is one of the most promising types of energy storage\cite{2-3}.

The compressed air energy storage system uses the compressor to pressurize the air to a higher pressure and then cool it and store it in the air storage tank at the low electricity consumption. At the peak of the electricity consumption, the air in the storage tank is heated to a certain temperature and then sent to the expander for power generation. Compared with other energy storage technologies, the compressed air energy storage system has the characteristics of large unit capacity, low unit power investment, long design life, etc. It has huge development potential\cite{4-5}.

At present, the research on compressed air energy storage is still in its infancy, and many thermal system characteristics, process control, and grid coupling characteristics need to be further mastered. At the same time, compressed air energy storage as a new form of energy storage, requires training to let more people understand its energy storage and energy release characteristics and work processes. However, the existing compressed air energy storage experimental platforms must be integrated into the power grid for experimental operations. Due to the large changes in experimental working
conditions and many sudden abnormal situations, when they are integrated into the power grid, they will easily disturb the safe operation of the power grid and cause safety risks. Therefore, it is necessary to develop an off-grid compressed air energy storage experimental platform to meet the above needs.

2. Compressed air energy storage experimental platform

The compressed air energy storage platform is divided into three layers. The top layer is equipped with air compressors and motors, air turbines and generators, operation monitoring boxes, and protective covers. The middle layer is equipped with electrical control boards and industrial computers, check valves, three-way valves, regulators Valves and related pipelines; High-pressure gas storage tanks are arranged on the bottom layer, as shown in Figure 1.

The electric motor (2) and the air compressor (3) are connected through a belt, the air turbine (4) and the generator (5) are connected through a belt or a shaft. The compressor inlet is connected to the atmosphere, the outlet is connected to the check valve (7) through a pipeline, the check valve is connected to the high-pressure gas storage tank (1) and the regulating valve (9) through the three-way valve(8) pipeline. The regulating valve is connected to the inlet of the air turbine through a pipe, and the outlet of the air turbine is connected to the atmosphere. In order to realize off-grid operation, this experimental platform designs a variety of high-power light bulbs (11) as loads, and changes the load size through electrical switches (10).

Fig. 2A and Fig. 2B are schematic diagrams of the three-dimensional structure of the CAES.

Fig. 1 Compressed air energy Storage experimental platform

Fig. 2A Oblique view of the three-dimensional structure of the compressed air experimental platform
3. **Main systems and parameters of the experimental platform**

Main technical characteristics of the experimental platform:

- The working range of compressor under variable conditions is 70-105%.
- The maximum pressure ratio of the compressor is 200.
- The working range of the expander under variable conditions is 30-105%.
- The maximum power generation is not less than 1kw.

It is mainly composed of four subsystems: gas storage system, energy storage and power consumption system, energy release and power generation system, and control and monitoring system.

### 3.1. Gas storage system

The function of the high-pressure gas storage tank is to store high-pressure compressed air. In the energy storage stage, the ambient air is pressurized by the air compressor and injected, and the energy is released to the air turbine in the energy release stage.

It adopts vehicle-mounted gas storage tank, the inner tank is aluminum alloy, and the outer surface is fully wound with carbon fiber.

**Table 1 gas storage system**

| Number | Equipment                  | Parameters         |
|--------|----------------------------|--------------------|
| 1      | Gas cylinder group         | Volume: 300L (6×50L) |

### 3.2. Energy storage and power consumption system

The role of energy storage and power consumption systems is to convert electrical energy into kinetic energy for storage. Mainly include air compressor, drive motor, etc. The air compressor uses a reciprocating piston air compressor with a rated pressure ratio of 200, and the motor uses a three-phase induction motor.

**Table 2 Energy storage and power consumption system**

| Number | Equipment | Parameters                      |
|--------|-----------|---------------------------------|
| 1      | Motor     | 5.5kW 50HZ 380V                 |
| 2      | Compressor| Air intake: normal temperature and pressure Exhaust: pressure 20MPa, temperature 25°C, flow rate 315L/min; |

### 3.3. Energy release and power generation system

The function of the energy release and power generation system is to convert kinetic energy into electrical energy. It mainly includes air turbine, transmission mechanism, intake valve generator, load, etc. The air turbine adopts a single-stage structure, and the bearing adopts solid lubrication. The generator is a synchronous AC three-phase generator with a self-excited constant voltage excitation method.
Table 3 Energy release and power generation system

| Number | Equipment          | Parameters                                      |
|--------|--------------------|-------------------------------------------------|
| 1      | Air turbine        | Inlet pressure: 0.5MPa                          |
|        |                    | Exhaust pressure: ambient pressure              |
|        |                    | Flow rate: 2.15m³/min                           |
| 2      | Transmission       | Transmission mode: pulley                       |
|        | mechanism          |                                                 |
| 3      | Intake valve       | Cv value: 0.05~1.05                             |
| 4      | generator          | Speed: 3000r/min, voltage: AC220V, power: 1kw   |
| 5      | load               | 1kw, AC220V, lighting lamp group                |

3.4. Control and monitoring system

The function of the control and monitoring system is to operate the automatic control and monitoring parameters of the experimental platform, including the control system and the monitoring system.

The automatic control system is mainly composed of electronic speed governor, excitation regulator and operation interface. The main parameters of the automatic control system are shown in Table 4.

The operation box realizes the functions of starting and stopping the motor, emergency shutdown of the system and grid connection of the generator. The operation monitoring box start and stop the motor has a "remote and local" switch to realize the local control of the operation monitoring box and remote computer control.

Table 4 Automatic control system

| Number | Equipment          | Parameters                                      |
|--------|--------------------|-------------------------------------------------|
| 1      | Electronic governor| Speed setting: 3000r/min                        |
|        |                    | Speed deviation: ±1%                           |
|        |                    | Speed regulation mode: closed loop regulation   |
| 2      | Excitation regulator| Excitation method: AC self-excitation          |
|        |                    | Voltage setting: 220V                          |
| 3      | Operation interface| 24-inch display                                 |

The monitoring system includes a high-pressure gas tank pressure gauge, a pressure gauge before the regulating valve, a pressure gauge after the regulating valve, an air turbine tachometer, a motor integrated power meter and a generator integrated power meter. The specific monitoring and control parameters are shown in Table 5.

Table 5 Monitoring control parameters

| Number | Monitoring control parameters |
|--------|-------------------------------|
| 1      | Air source pressure (MPa)     |
| 2      | Air source temperature (°C)   |
| 3      | Temperature after pressure reducer (°C) |
| 4      | Pressure after pressure reducer (MPa) |
| 5      | Expander intake air flow (m³/min) |
| 6      | Expander inlet temperature (°C) |
| 7      | Expander inlet pressure (MPa) |
| 8      | Expander speed (r/min)        |
| 9      | Speed control valve opening (%) |
|   |                                                                 |
|---|-----------------------------------------------------------------|
| 10 | Energy storage phase A voltage (V), current (A), active power (kW) |
| 11 | Energy storage phase B voltage (V), current (A), active power (kW) |
| 12 | Energy storage phase C voltage (V), current (A), active power (kW) |
| 13 | Total phase active power of energy storage (kW)                  |
| 14 | Energy storage phase A power factor                              |
| 15 | Energy storage phase B power factor                              |
| 16 | Energy storage phase C power factor                              |
| 17 | Energy storage frequency (HZ)                                    |
| 18 | Discharge phase A voltage (V), current (A), active power (kW)    |
| 19 | Discharge phase B voltage (V), current (A), active power (kW)    |
| 20 | Discharge phase C voltage (V), current (A), active power (kW)    |
| 21 | Discharge phase A power factor                                   |
| 22 | Discharge phase B power factor                                   |
| 23 | Discharge phase C power factor                                   |
| 24 | Discharge frequency (HZ)                                         |

4. Off-grid load
This experimental platform uses multiple sets of high-power light bulbs as loads. The high-power bulbs include halogen bulbs, tungsten bulbs, and infrared bulbs.

The power of each group of high-power bulbs can be the same or different. Generator output power and high-power bulb power meet the following requirements:

\[
W_{out} = \sum_{i=1}^{n} W_i \quad i = 1, 2, 3...n
\]

Where, \(W_{out}\) represents the generator output power, \(i\) represents the number of high-power bulbs, \(n\) represents the amount of high-power bulbs, and \(W_i\) represents the power of the \(i\)-th group of high-power bulbs.

Using high-power light bulbs as a load has the following advantages:
1. Solve the problem that the compressed air energy storage experimental platform has large changes in experimental working conditions and many sudden abnormal situations, and it will easily disturb the safe operation of the power grid when it is integrated into the power grid.
2. Simple structure and low cost.
3. The lamp has a wide adaptable voltage range. Putting the lamp in sequence as a load can realize the adjustment of the full power range of the generator, which is easy for experimental control.
4. Observe the power of the generator through the brightness of the bulb, which is easy to observe the experimental results.
5. Use a lamp to illuminate the high-pressure gas storage tank to the air turbine inlet pipe, and use the heat of the lamp to increase the inlet temperature to prevent the drop of the inlet temperature from causing the experiment to be interrupted.

5. Experimental process and method

5.1. Start and stop the experiment process
The process of starting and stopping the experiment includes starting and stopping the energy storage
process and starting and stopping the energy release process. The method to start the energy storage process is: start the motor to drive the air compressor to adiabatic compress the air at room temperature and pressure to produce high temperature and high pressure air, close the regulating valve, and the high pressure air enters the high pressure air tank through the check valve and the three-way valve. The method to stop the energy storage process is as follows: stop the motor and air compressor, and the check valve ensures that the high-pressure air will not flow from the high-pressure storage tank to the air compressor when the air compressor is stopped.

The method to start the energy release process is as follows: open the control valve, the high-pressure gas from the high-pressure gas storage tank enters the air turbine through the high-pressure three-way and the control valve for adiabatic expansion, and outputs mechanical energy to drive the air turbine to the rated speed, and the generator generates electricity. Connect the load with light bulb by putting in the electric switch. The method of stopping the energy release process is: closing the regulating valve, and stopping the operation of the air turbine and generator.

5.2. Load adjustment method

5.2.1 The method of increasing the load is as follows:
When the power generation and the high-power bulb load are balanced, calculate the preset value of the opening of the compressed air intake control valve:

$$\Delta l = \left(1 + \frac{W_l}{W_t} \times 50\%\right) l_r$$

Where, $\Delta l$ is the valve preset value, the unit is %, $W_l$ is the power to be put into a group of high-power bulbs, $W_t$ is the rated power of the expansion generator, and $l_r$ is the current valve opening value, the unit is %.

Put in the group of high-power bulbs, and adjust the opening of the compressed air intake control valve to the preset value.

The power generation of the expansion generator increases, the new high-power bulb lights are brightened, the speed of the expansion generator decreases, and the system frequency decreases. Continue to increase the opening of the compressed air intake control valve until the power generation and the high-power bulb load balance. The brightness of the high-power bulb is normal, the speed of the expansion generator reaches the rated value, and the system frequency reaches the rated value.

5.2.2 The method of reducing the load is as follows:
When the generated power and the load of the high-power bulb are balanced, the preset value of the opening of the compressed air intake control valve is calculated as:

$$\Delta l = \left(1 - \frac{W_l}{W_t} \times 80\%\right) l_r$$

Where, $\Delta l$ is the valve preset value, the unit is %, $W_l$ is the power of a group of high-power bulbs to be cut off, $W_t$ is the rated power of the expansion generator, and $l_r$ is the current valve opening value, the unit is %.

Cut off the group of high-power bulbs, and adjust the opening of the compressed air intake control valve to the preset value.

The power generated by the expansion generator is reduced, the high-power bulb lamp that was removed is extinguished, the speed of the expansion generator increases, and the system frequency increases. Continue to reduce the opening of the compressed air intake control valve until the power generation and the high-power bulb load balance, the speed of the expansion generator reaches the rated value, and the system frequency reaches the rated value.

6. Conclusion
By building a new type of compressed air energy storage experimental platform, it meets the requirements of experimental research and training, and has the following characteristics:

1 It can completely simulate the whole process of compressed air power consumption and energy
storage, power generation and energy release, and the operation and monitoring system is complete.

2 Off-grid operation to prevent large changes in working conditions and sudden abnormal conditions from affecting the safety of the power grid during the experiment.

3 The system is simple and compact, low cost, and has the function of load pre-adjustment operation.

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