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# Research on the Static Test of Active Power Compensation Coefficient for Compressed Air Energy Storage

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**Abstract.** Peak load regulation and frequency regulation of electric power system are the main roles of Compressed Air Energy Storage (CAES). The static test method to active power compensation coefficient (APCC) has never been founded yet. Based on the operation character of CAES, the range of APCC has been given in this paper. This paper also introduced the static test system for APCC and the process of static test. In the end, the method of calculating for APCC has been established. With the static test, the APCC can be evaluated, which can make the grid more stable.

## 1. Introduction

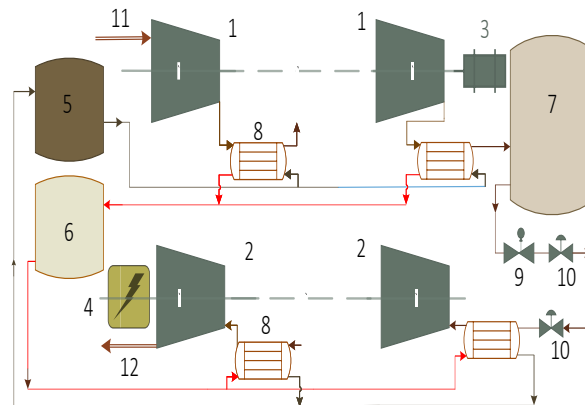
Large-scale power storage technology is an effective way to solve the problem of new energy generation [1,2], and Compressed Air Energy Storage (CAES) is considered as one of the most promising power storage technologies due to its advantages of large energy storage scale, small environmental pollution, long storage cycle, etc. [3].

There are many ways to achieve Compressed Air Energy Storage (CAES). In China, researchers mostly focus on non-combustion compressed air storage, and they mainly research on the compressed air energy storage system, however, no research has been reported on the operation performance when CAES participate in the peak and frequency modulation of power grid. Adjustment coefficient is an important parameter of primary frequency modulation, which can reflect the relationship between the system frequency changes and power changes, and has a great influence on maintenance of the stability of system frequency, there are lots of clear test methods on the current forms of the traditional power generation such as thermal power, hydropower, gas turbine, furthermore, the static test must be completed and qualified before starting the unit, but regulations on compressed air energy storage system have still not been proposed, so, some relevant researches is needed to formulate the test systems, test methods and eligibility criteria of CAES.

## 2. Non-combustion Compressed Air Energy Storage System

In order to improve the system efficiency, the non-combustion compressed air energy storage system is generally multi-stage. See figure 1 for the system figure.





1-multistage compressor, 2- multistage expander, 3- motor, 4- generator, 5- cold storage tank, 6- heat storage tank, 7- compressed air tank, 8- heat exchanger, 9- main air valve, 10- regulating air valve, 11- air entry, 12- exhaust

**Figure. 1** Multi-stage adiabatic compressed air energy storage system

When grid power is rich, start the air compressor power consumption process: Air enters the compressor for compression, and the compressor is driven by the motor, there is a lot of heat when the air is compressed, the compressed air enters the heat exchanger, then the cooling medium takes the heat away, after the compressed air temperature drops, it enters the next stage for another compression. After multi-stage compression, the air pressure rises and then the high-pressure air is stored in storage tanks, the heat exchange medium recovers heat to the heat storage tank. When the grid power shortage, start the air power expansion process: compressed air enters the expander for expansion and drive the generator to generation. After this work, the compressed air with a temperature drop is heated in the heat exchanger, and then enters the next stage of the turbine for power generation. After multi-stage expansion, it is discharged into the atmosphere.[4].

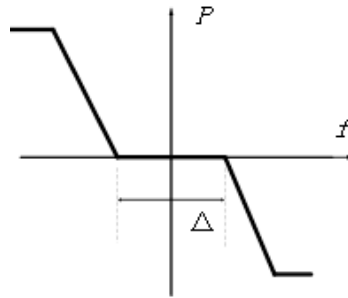
The adjustment system of the expander consists of an electric main air valve and two Pneumatic control regulating valves (in series), while the expander running, the adjustment system adjusts the valves opening according to the speed or power, to control the amount of compressed air intake, and the expansion generator from start to rated speed in the start-up phase, after grid connection, the adjustment system control the output power of expansion generator according to the grid dispatching command.

### 3. Grid primary frequency modulation and adjustment coefficient

#### 3.1. Grid primary frequency modulation

Primary frequency modulation of power system refers to the regulation method that uses the inherent load frequency characteristics of the system and the role of the generator set's governor to prevent the system frequency from deviating from the standard.

The speed of all generator sets in the system changes when the power system frequency  $f$  changes. For example, if the change value of frequency  $\Delta f$  exceeds the insensitive zone B (dead zone) stipulated by the generator set, the speed regulating system of the generator set will act, change the inlet adjusting door opening of the prime mover, adjust the power of the prime mover, and improve the unbalanced condition of the prime mover's power or load. That is, when the system frequency decreases, the opening degree of the prime mover's inlet adjusting door will increase, increasing the power  $P$  of the prime mover. In addition, when the system frequency increases, the opening degree of the prime mover's inlet adjusting door will decrease, reducing the power of the prime mover [5], as shown in figure 2.



**Figure. 2** principle of primary frequency modulation

### 3.2. Active Power Compensation Coefficient

The relationship between frequency variation and power variation in the system is usually expressed by the adjustment coefficient R:

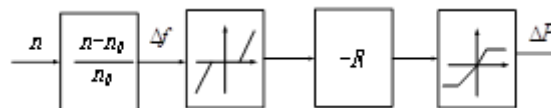
$$R = \frac{\Delta P / P_e}{\Delta f / f_e} = \frac{(P_e - P_a) / P_e}{(f_e - f_a) / f_e} = \frac{(P_e - P_a) / P_e}{(n_e - n_a) / n_e} \quad (1)$$

Where  $\Delta P$  is System load change value caused by system frequency change, and  $\Delta f$  is System frequency change value, and  $f_e$  is System rated frequency, and  $f_a$  is Actual operating frequency, and  $P_e$  is Generator rated power, and  $P_a$  is Actual operating power of the generator, and  $n_e$  is System rated speed, and  $n_a$  is Actual operating speed.

It is also expressed by the speed unequal rate (speed change rate)  $\delta$ , and the relationship is:

$$\delta = \frac{1}{R} \quad (2)$$

The primary frequency modulation function of the generator set is mainly composed of four components, which are frequency difference, dead zone, adjustment and clipping. The transfer function is shown in Figure 3.



**Figure. 3** Primary frequency transfer function

It can be known from formula (1): For a single unit, the unit has a large load variation and poor stability when its adjustment coefficient R is large (small speed unequal rate  $\delta$ ), the load change caused by the unit is large and the unit's stability is poor. In addition, the load change caused by the unit is small and the unit's stability is good when its adjustment coefficient R is small (large speed unequal rate  $\delta$ ). Generally, the adjustment coefficient setting of the unit with basic load is small, and the adjustment rate of the frequency modulation unit is set larger.

<<Power Grid Standards>> [6] stipulates that the speed difference  $\delta$  is 4%~5% for the thermal power unit and the gas turbine, and not more than 4% for the hydropower unit. The reason of that is the start-stop speed of the thermal power unit is slow. In order to ensure the safe operation of gas turbine, the primary frequency modulation performance requirements of thermal power units and gas turbine are relatively low, mainly with basic load. The hydropower unit has flexible operation, quick start, and strong ability to follow the load. It only takes a few minutes to start up to the rated power, and its frequency modulation performance is good. The hydropower unit is the main unit of frequency modulation.

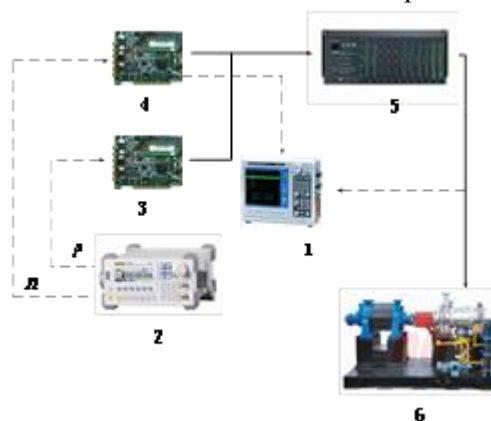
The compressed air energy storage starts quickly, only takes a few minutes from standstill to rated power, and is not subject to the expansion of combustion high-temperature components during operation according to its characteristics. The load regulation speed can reach 20% ECR/min

(Economic Continuous Rating). Its load variation ability is strong, and the role in the power grid is frequency and peak load modulation. So the speed unequal rate can be set to 3~4% with reference to the hydropower unit, that is, the adjustment coefficient is 25~33.

#### 4. Adjustment coefficient test system

The adjustment coefficient test mainly involves the speed measurement link, the power measurement link and the power control link.

Since there is no power output signal for the unit static test, the power controller output is used for test calculation, but it needs to be marked. The test system diagram is shown in figure 4. The signal generator outputs the speed and power analog signals to the speed acquisition and measurement device and the power acquisition and measurement device respectively. The wave recorder records the output signals of the speed acquisition and measurement device and the power controller.



1- wave recorder, 2- Signal Generator, 3- Power Acquisition and Measurement Unit, 4- Speed Acquisition and Measurement Unit, 5- Power Controller, 6- Expansion Generator  
Solid Line - Official Connection Line Dotted Line - Test Connection Line

**Figure. 4** Test system diagram

#### 5. Adjustment coefficient testing process and result analysis

##### 5.1. Testing process

The expansion generator is connected to the grid in the thermal control logic, the power signal for dispatching is closed, the input power control loop is automatically controlled, the primary frequency modulation is input, and the set value in the logic is retained. The wave recorder uses a sampling rate of 1000 Hz to record the speed signal and the power control loop output signal.

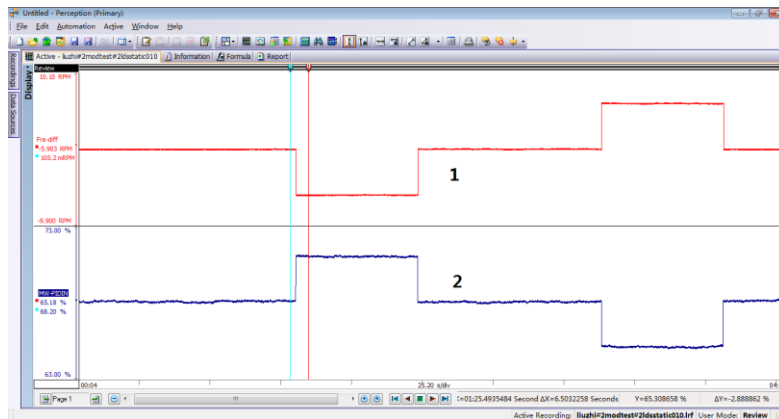
Signal generator simulates power  $P_e$ , power controller input power instruction is  $P_e$ , record power controller output current  $I_e$ , as the basic value of power signal's per unit calculation.

The signal generator is used to add speed analog signal  $n_e$  to the speed acquisition and measurement device, and power analog signal  $P_0$  to the power acquisition and measurement device.

Speed drop test: The signal generator is used to ramp the speed analog signal from the  $n_e$  step to  $n_1$ , and the power control loop output signal should up to  $I_1$ . Record the entire process with the wave recorder.

The signal generator restores the speed analog signal to  $n_e$ .

Speed rise test: The speed analog signal is simulated to jump from the  $n_e$  step to  $n_2$  by the signal generator, and the output signal of power control loop should drop to  $I_2$ . The entire process was recorded with the wave recorder, and the test results are shown in figure 5.



1— Speed signal,2- Power controller output signal

**Figure. 5** Test system diagram

### 5.2. Result calculation analysis

The calculation formula (3) for speed drop test and the calculation formula (4) for speed rise test are derived according to formula (2). Then the adjustment coefficient is calculated according to the test data.

$$R_{down} = \frac{(I_1 - I_e) / I_e}{(n_e - n_1) / n_e} \quad (3)$$

$$R_{up} = \frac{(I_e - I_2) / I_e}{(n_2 - n_e) / n_e} \quad (4)$$

The qualified standards of the test are:

$$R_{down} = R_{up} = R_{set} \quad (5)$$

That is, the results which calculated according to equations (3) and (4) should be equal and close to the set value, otherwise, the thermal control logic should be checked and retested until the results are qualified.

## 6. Conclusion

Compressed air energy storage system power regulation speed, mainly responsible for the grid peak frequency modulation task. According to the operation characteristics of compressed air energy storage system, the scope of the controlled system, by using wave record meter and signal generator, build the expansion generator controlled system static testing system, formulate the static test of test preparation, speed down/up the testing process, calculation method and standard as a result, in front of the unit based on static test of primary frequency control system of the differential coefficient of parts for inspection, guarantee to stable operation of power grids.

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