Off-design Characteristics for Expansion Power Generation Process of Liquid Air Energy Storage System

Guizhi Xu\(^1\), Zhanfeng Deng\(^1\), Shuangshuang Cui\(^2\), Xingping Shi\(^2\), Chang Lu\(^2\), Lixiao Liang\(^1\) and Qing He\(^2\)*

\(^1\)Global Energy Interconnection Research Institute Co. Ltd, Beijing 102209, China
\(^2\)School of Energy Power and Mechanical Engineering, North China Electric Power University, Beijing 102206, China

*Corresponding author email: heq@ncepu.edu.cn

Abstract. In order to study the off-design conditions of energy storage system due to the grid load requirements and the fluctuation of external environmental factors in the process of grid-connected operation and the off-design performance of energy storage system, the dynamic model of expansion power generation of 500kW liquid air energy storage (LAES) system is established. Considering the change characteristics of the adiabatic efficiency and pressure ratio of the expander with flow rate, the dynamic changes of rotor speed, electric power, and valve opening size of LAES system under complex conditions of increasing/decreasing load are simulated. The results show that the stability time of electric power is shorter when the variable load is lower when the load change rate of the energy storage system is kept constant under the condition of increasing/decreasing load. On the contrary, the stability time of electric power is longer when the variable load is higher. The stability time of electric power is 12s when the energy storage system changes from 100% rated condition to 90% working condition. The stability time of electric power is 34s when the energy storage system changes from 100% rated working condition to 60% working condition. Under the condition of variable load, the fluctuation of rotor speed is very small and remains unchanged.

1. Introduction

With the rapid rise of new energy power generation and the increasing penetration rate, the characteristics of intermittence and volatility pose severe challenges to the safe and stable operation and dispatching of the existing power system. At present, China is forming a new pattern of energy development. It has become the task of the times to promote the green energy revolution, accelerate the transformation of energy structure, and improve the efficiency of energy utilization. In order to absorb more new energy and improve the reliability and efficiency of power grid operation, various energy storage technology research and demonstration projects have developed rapidly [1]. Common energy storage technologies include pumped storage, electrochemical energy storage, flywheel energy storage, and compressed air energy storage (CAES). According to their working principles, CAES can be roughly divided into traditional CAES, advanced adiabatic CAES, and liquid air energy storage (LAES) [2]. Among them, the LAES technology is based on the advanced adiabatic CAES technology, which applies the cold storage technology and air liquefaction technology to the energy storage system. It has the advantages of high energy storage density, low storage pressure, the use of independent storage tanks to replace underground salt caverns for electric energy storage, which gets rid of the restriction of geological conditions, and makes it suitable for all links of power system generation,
transmission, distribution and use.
Up to now, the research on the LAES system is limited to design analysis and thermodynamic calculation. For example, He et al [3] established the thermodynamic model of the main components of the LAES system, and analyzed the system through analytical methods. The analysis results show that the LAES system with four-stage compression and four-stage expansion has good comprehensive thermodynamic performance, and determine the unit with the greatest loss and the optimal value of each main parameter. Peng et al [4] of Birmingham University put forward a new energy storage system combining liquefied natural gas (LNG) with LAES system, aiming at the low cycle efficiency of the LAES system. The results show that compared with the independent LAES system, the liquefaction rate of the new energy storage system is as high as 89%, and the energy consumption per unit mass of liquefied air is reduced by about 32%. However, the research on dynamic characteristics is relatively few, and it only focuses on CAES. For example, Li et al [5] studied the dynamic response of energy storage system when it participated in power grid frequency regulation by establishing the dynamic model of advanced CAES system and the control model of grid-connected speed regulation system and obtained the optimized control strategy by analyzing the response under typical disturbance. However, at present, there is little research on the dynamic characteristics of LAES, and there is a lack of in-depth research on the off-design characteristics of the expansion power generation system, which seriously limits the development and popularization of LAES technology.

In order to study the off-design problems of energy storage system caused by a series of factors, such as grid load requirements, fluctuation of external environmental factors, and variability of unit components, and master the off-design performance of energy storage system, this paper takes the expansion power generation system with 500kW LAES as the research object, establishes the system dynamic model by using simulation software, and simulates the dynamic changes of rotor speed, electric power and valve opening of energy storage system during load increase/decrease.

2. LAES System
LAES is a device that converts surplus electricity or abandoned wind and light electricity into the internal energy of liquid air for energy storage. A schematic diagram of the LAES system is shown in Fig.1.

![Figure 1. Schematic diagram of LAES system](image)

Because the expansion process is independent of the process of compression and liquefaction of the LAES system, the compression process and liquefaction process do not participate in the work when releasing energy. Therefore, only the expansion process needs to be considered in the research process.
of this paper. Also, the system adopts a four-stage expansion. The operating parameters of the expansion process of the LAES system are shown in Table 1.

| Item                              | Stage | 1     | 2     | 3     | 4     |
|-----------------------------------|-------|-------|-------|-------|-------|
| Medium                            |       | Air   | Air   | Air   | Air   |
| Flow, Nm$^3$/h                    |       | 5600  | 5600  | 5600  | 5600  |
| Inlet pressure, MPa (A)           |       | 10.0  | 4.09  | 1.64  | 0.435 |
| Outlet pressure, MPa (A)          |       | 4.1   | 1.65  | 0.45  | 0.12  |
| Inlet temperature, °C             |       | 110   | 110   | 110   | 110   |
| Outlet temperature, °C            |       | 39.2  | 36.3  | 9     | 7.6   |
| Efficiency, %                     |       | 78    | 82    | 84    | 86    |
| Output power of expander, kW      |       | 134   | 143.7 | 199.6 | 204.4 |
| Efficiency of generator, %        |       |       |       |       | 93    |
| Rotating speed, r/min             |       |       |       | 1500  |       |
| Rated power, kW                   |       |       |       | 630   |       |
| Output power, kW                  |       |       |       | 540   |       |

3. Model

3.1. Expander

The actual air expansion process is complicated. Based on the isentropic expansion hypothesis, this paper models the working process of the expander. The output power of the expander is:

$$W_e = m_e (h_{in,e} - h_{out,e})$$

where, $m_e$ is the mass flow of air in the expander, kg/s; $h_{in,e}$ is the enthalpy of air entering the expander, kJ/kg; and $h_{out,e}$ is the enthalpy of air exiting the expander, kJ/kg.

Besides, when the expander is running under off-design conditions, the expansion ratio and efficiency change with the change of flow rate, rotor speed, and other parameters. Reference [6], the expander is compared with the nozzle, and the flow characteristic formula of the expander is calculated according to the Flugel formula:

$$ \dot{G}_i = \sqrt{1.4 - 0.4 \dot{n} \sqrt{(1/\pi_i - 1)/(1/\pi_{in} - 1)}}$$

where, $\dot{G}_i$ is the relative flow rate; $\dot{n}_i$ is the relative rotor speed; $\pi_i$ is expansion ratio; and $\pi_{in}$ is rated expansion ratio.

Adiabatic efficiency is:

$$\eta_i = [1 - t_4 (1 - \dot{n}_i)^2] (\dot{n}_i / \dot{G}_i)(2 - \dot{n}_i / \dot{G}_i)$$

where, $\eta_i$ is adiabatic efficiency; and $t_4$ is a coefficient with a value of 0.3[5].

3.2. Heat Exchanger

According to the energy conservation theory, the exchange equation between the cold and heat of the heat exchanger is:

$$m_c c_c (T_{c,in} - T_{c,out}) = c_h (T_{h,in} - T_{h,out})$$

where, $m_c$ is the mass flow of cold flow in heat exchanger, kg/s; $c_c$ is the specific heat capacity of cold flow, J/(kg·K); $T_{c,in}$ is the inlet temperature of the cold flow, K; $T_{c,out}$ is the outlet temperature of
the cold flow, $K$; $\varepsilon$ is the efficiency of the heat exchanger; $m_h$ is the mass flow of hot flow in heat exchanger, kg/s; $c_h$ is the specific heat capacity of hot flow, J/(kg·K); $T_{inh}$ is the inlet temperature of the hot flow, K; and $T_{outh}$ is the outlet temperature of the hot flow, K.

### 3.3. Generator

In order to simplify the simulation difficulty and meet the requirements of control accuracy and influence analysis of various parameters, the single machine infinite power grid model is adopted in the simulation. In the model, the excitation control is simplified, and the assumption that the no-load potential of the generator is constant is adopted. There is a generator power equation:

$$ R_q = \frac{E_q V_s}{\chi_d \Omega} \sin \theta $$  \hspace{1cm} (5)

where, $\theta$ is the power angle of the synchronous generator; $V_s$ is the voltage of the power grid, V; $\chi_d$ is reactance, $\Omega$; and $E_q$ is no-load electromotive force.

After deduction, the transfer function of the single machine infinite power grid system is obtained as follows [6]:

$$ \frac{\Delta P_e}{\Delta \eta} = D + \frac{K_q \omega_0}{s} $$  \hspace{1cm} (6)

where, $\Delta P_e$ is generator power, W; $\Delta \eta$ is the speed of expander, r/min; $D$ is the electromagnetic damping coefficient, generally 4~25; and $\omega_0$ is the rated angular velocity.

### 4. Results and Discussion

According to the flow characteristic formula of the expander and relevant design parameters, the pressure ratio and adiabatic efficiency of expander corresponding to different relative flow rates and relative rotor speeds are calculated, as shown in Fig.2.

![Graphs showing pressure ratio and adiabatic efficiency](image)

**Fig.2.** Pressure ratio and adiabatic efficiency of expander vs. relative flow rates and relative rotating speed

Fig.2 describes the variation of relative pressure ratio and relative adiabatic efficiency of the expander with flow rate and rotor speed. It can be seen from Fig.2(a) that the relative pressure ratio of expander increases with the increase of relative flow rate, and the closer the relative flow rate is to 1, the greater the increase of relative pressure ratio. When the flow rate remains constant, the relative pressure ratio of expander decreases with the increase of rotor speed. It can be seen from Fig.2(b) that the relative adiabatic efficiency of the expander first increases and then decreases with the increase of mass flow rate. When the relative flow rate is close to 1, the relative adiabatic efficiency decreases gradually with the increase of relative rotor speed.

The flow characteristics and initial parameters of the expander are brought into the simulation model. Under the condition of ensuring the stable operation of the unit connected to the grid, the simulation is
carried out according to the power regulation requirements. That is, in the simulation process, a power adjustment signal was input at 3500s, and the electric power was adjusted by adjusting the valve opening of the control system, which in turn simulated the dynamic changes of the energy storage system from 100% rated working conditions to 60%, 70%, 80%, 90%, 110% and 120% working conditions respectively. The parameter change from 100% working condition to 90% working condition is shown in Fig.3.

The simulation process of the other five groups of load increase/decrease is similar to Fig.3. Based on the results of these six groups of simulation experiments, the changes of electric power, rotating speed, valve opening, and other related parameters of the LAES system under off-design conditions can be obtained, as shown in Table 2.

![Graphs showing changes in electric power, rotor speed, and valve opening over time](image)

**Figure 3.** The parameter change from 100% working condition to 90% working condition

**Table 2.** The relative parameters of the LAES system under off-design conditions

| Variable condition, % | Stability time of electrical power, s | The maximum or minimum of speed scale unit value | Valve opening scale unit value |
|-----------------------|--------------------------------------|-----------------------------------------------|-----------------------------|
| 100-60                | 34                                    | 0.999253                                      | 0.92                        |
| 100-70                | 28                                    | 0.999253                                      | 0.94                        |
| 100-80                | 17                                    | 0.999255                                      | 0.96                        |
| 100-90                | 12                                    | 0.999256                                      | 0.98                        |
| 100-110               | 13                                    | 1.000751                                      | 1.02                        |
| 100-120               | 18                                    | 1.000751                                      | 1.03                        |

It can be seen from Fig.3 and Table 2 that when the energy storage system increases/decreases the load while the load change rate remains unchanged, the stability time [5] of electric power changes with the change of working conditions. The smaller the change, the shorter the stability time of electric power, and the longer the stability time of electric power in the larger the change. For example, when the energy storage system changes from 100% rated working condition to 90% working condition, the stability time of electric power is 12s, while when the energy storage system changes from 100% rated working condition to 60% working condition, the stability time of electric power is 34s. When running under variable load conditions, the fluctuation of rotor speed is very small and remains unchanged. For
example, the fluctuation of the speed scale unit value of the energy storage system during load increase/decrease is about 0.00075. Also, since the valve opening directly affects the gas flow and pressure entering the expander, and the expansion ratio and isentropic efficiency change with the rotor speed and gas flow, the relationship between the valve opening scale unit value and the electric power scale unit value is not a standard proportional relationship. When the energy storage system changes from 100% rated working condition to 60% working condition, the scale unit value of valve opening changes from 1 to 0.92. When the valve opening scale unit value changes from 1 to 1.1, the electric power scale unit value changes from 1 to 1.02.

5. Conclusions
(1) By comparing the expander with the nozzle, the relative pressure ratio and relative adiabatic efficiency of the expander with the flow rate and rotor speed are calculated according to the Flugel formula. The relative pressure ratio increases with the increase of relative flow rate, and the closer the relative flow rate is to 1, the greater the increase of relative pressure ratio. When the flow rate remains unchanged, the relative pressure ratio decreases with the increase of relative speed. The relative adiabatic efficiency first increases and then decreases with the increase of mass flow rate. When the relative flow rate is close to 1, the relative adiabatic efficiency decreases with the increase of relative rotating speed.

(2) When the energy storage system increases/decreases the load under the condition that the load change rate remains unchanged, the stability time of electric power is shorter when the load is increased/decreased smaller, and longer when the load is increased/decreased larger. When the energy storage system changes from 100% rated working condition to 90% working condition, the stability time of electric power is 12s, while when the energy storage system changes from 100% rated working condition to 60% working condition, the stability time of electric power is 34s. When running under variable load conditions, the fluctuation of rotor speed is very small and remains unchanged.

Acknowledgement
This work is supported by the Science and Technology Project of State Grid Corporation of China (2018-2020-SGGR0000DLJS1801307).

References
[1] Li Jianlin, Ma Huimeng, Hui Dong. Present development condition and trends of energy storage technology in the integration of distributed renewable energy. Transactions of China Electrotechnical Society, 2016, 31(14): 1-10.
[2] Dong Zhou, Li Kai, Wang Yongsheng, Wang Ning, Zhu Qing. Research and application status of CAES technology. Hebei Electric Power, 2019, 38(5): 18-20.
[3] He Qing, Wang Lijian, Zhou Qian, Lu Chang, Du Dongmei, Liu Wenyi. Thermodynamic analysis and optimization of liquefied air energy storage system. Energy, 2019, 173: 162-173.
[4] Xiaodong Peng, Xiaohui She, Chuan Li, Yimo Luo. Liquid air energy storage flexibly coupled with LNG regasification for improving air liquefaction. Applied Energy, 2019, 250: 1190-1201.
[5] Pan Li, Chen Yang, Li Sun, Jinyao Xiang, Xiankui Wen, Jingliang Zhong, Tongtian Deng. Dynamic characteristics and operation strategy of the discharge process in CAES systems for applications in power systems. International Journal of Energy Research, 2020, 44(8): 6363-6382.
[6] Zhewu Cheng. Research on off-design performance analysis and design optimization of low-temperature adiabatic CAES system. Zhejiang University, 2019, 27-73.