Power Regulation Strategy of Virtual Pumped Storage Power Station Based on Compressed Air Energy Storage

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Abstract. The virtual pumped storage power station based on compressed air energy storage combines compressed air energy storage and pumped storage technology organically, complements each other's advantages, and adopts efficient hydraulic equipment to compress air. In the process of power regulation, the head of high-pressure pool is controlled to be constant, the efficiency of pump-turbine unit is improved, and the power station is operated efficiently and steadily. In this paper, a 1 MW pumped storage power station is designed, and the power regulation strategy for stable operation of power generation and electric conditions is put forward. The mathematical model of each module of the power station is established. According to the power regulation instructions, the ideal values of the operation parameters of the power station are calculated, and the regulation instructions are given to the driving equipment of the hydraulic transformer. The running process of the hydraulic piston and the fluctuation of the head of the high-pressure pool are also simulated and analyzed, which verifies the feasibility of the strategy.

1. Introduction
With renewable energy such as wind power and photovoltaic connected to the power grid, it has become an urgent need for power grid operation and control to realize power balance by flexible energy storage system. Among the existing energy storage technologies, pumped storage and compressed air storage are two main technologies to realize large-scale energy storage. The position of compressed air energy storage is flexible and simple, but the main engine of gas turbine can not rotate. Fuel consumption rate is high and efficiency is low. Pumped storage uses efficient hydraulic equipment, which has high reliability and flexibility. It has the functions of peak shaving, Valley filling, phase adjustment and black start, but it is strictly limited by geographical factors. Therefore, a virtual pumped storage power station based on compressed air energy storage is proposed, which combines compressed air energy storage technology with pumped storage technology to complement each other's advantages [1, 2].

For the traditional pumped storage power station, under the electric condition, because of the restriction of water head, the power can not be regulated. When the speed of the unit is too low, the pump can not pump water to the upper reservoir for energy storage. Therefore, the traditional pumped storage power station can not operate on an isolated island, and it needs a standby power supply under the electric condition. Since the early 1990s, it has been applied in engineering and gradually realized the continuous speed regulation of Large Pumped Storage units. At present, the variable frequency speed control unit is used to adapt to different running water heads by changing the speed [3, 4]. Many scholars
at home and abroad have also studied the doubly-fed pumped storage unit, established the mathematical model of the unit, and simulated the dynamic characteristics of active power in stable operation of power generation and electric conditions [5, 6]. Although the improvement of generating units has properly increased the head variation, the large-scale change of the head of large-capacity power plants still reduces the efficiency of generating units.

The virtual pumped storage power station based on compressed air energy storage provides virtual water head for pumped storage power station by using high-pressure pool feed water pump turbine generator set. The fixed water head of high-pressure pool makes the pump turbine run stably and efficiently. In this paper, the parameters of each module are designed, and the mathematical models of each module of the power station under the power generation and electric conditions are established. According to the power regulation instructions, the ideal values of the parameters of the power station are calculated, and the regulation instructions are given to the driving equipment of the hydraulic transformer to control the hydraulic potential. It can change the running speed of the hydraulic piston in the system to make the head of the high-pressure pool constant.

2. Power plant design

2.1. Power Plant Structure
The virtual pumped storage power station based on compressed air energy storage includes fixed head pumping system, hydraulic potential energy conversion system, isothermal compression system and constant pressure storage system. The fixed-head pumping and storage system consists of reversible pump-turbine power generation motor set, water diversion pipeline, high-pressure pool and low-pressure pool. Hydraulic potential energy conversion system is composed of several groups of hydraulic transformers and driving equipment. Isothermal compression system consists of chemical tower. Constant pressure storage system is composed of gas storage device [1]. As shown in Figure 1.

![Virtual pumped storage power station based on compressed air energy storage.](image)

Figure 1. Virtual pumped storage power station based on compressed air energy storage.

When the load of the power grid changes, it is necessary to control the joint operation of each module of the power plant, so that the operation parameters of the power plant match the power instructions, so as to control the head stability of the high-pressure pool.

2.2. Parameter Design
Taking the parameters of Pumped Storage Generator Unit of Cuntangkou Hydropower Station as an example, the technical parameters of pump turbine are shown in Table 1 [7].
Table 1. Technical parameters of pump turbine.

| Pump-turbine unit | Design Head (m) | Design Flow (m³/s) | Maximum Head (m) | Minimum Head (m) | Rated Power (kW) |
|-------------------|----------------|-------------------|-----------------|-----------------|-----------------|
| Hydraulic Turbine | 31             | 4.04              | 33.6            | 21              | 1063            |
| Water Pump        | 37             | 2.79              | 40              | 27              | 1110            |

Five sets of hydraulic transformers are needed for power generation and energy storage in the operation of the power station designed in this paper. The parameters of the piston hydraulic cylinder are designed according to (1).

\[ P_n = Fv = P_2S_2v = P_2Q_1 \]  

Among them, \( P_n \) is the output power of the hydraulic transformer, \( F \) is the output force of the piston rod, \( v \) is the running speed of the piston rod, \( P_2 \) is the pressure of the high-pressure pool, \( S_2 \) is the cross-section area of the piston hydraulic cylinder connected with the high-pressure pool, and \( Q_1 \) is the flow rate of the high-pressure pool into the turbine. The design parameters of the hydraulic transformer are shown in Table 2.

Table 2. Hydraulic transformer parameters.

| Pump-turbine unit | Design Head (m) | Design Flow (m³/s) | Maximum Head (m) | Minimum Head (m) | Rated Power (kW) |
|-------------------|----------------|-------------------|-----------------|-----------------|-----------------|
| Hydraulic Turbine | 31             | 4.04              | 33.6            | 21              | 1063            |
| Water Pump        | 37             | 2.79              | 40              | 27              | 1110            |

The high pressure pool is designed as a cylindrical tank, and its parameters are shown in Table 3.

Table 3. High Pressure Pool Parameters.

| Volume V (m³) | Bottom Area S (m²) | Height (m) | Rated Head Height \( h_0 \) (m) |
|--------------|-------------------|------------|------------------|
| 2            | 1.2               | 1:3        | 5                |

3. Power regulation strategy

3.1. Model Establishment

3.1.1. Electric working condition model. The relationship between pump input power \( N_p \) and pump head \( H \) and flow \( Q \) is [8],

\[ N_p = 9.81HQ/\eta (kW) \]  

From Table 1, it can be seen that the maximum pump lift is 40 m, the minimum pump lift is 27 m, and the design lift is 37 m. The regulation range of the pump lift is 0.73-1.081 when expressed by the standard unitary value. The relationship between pump head and input power is as follows,

\[ H = kN_p^{2/3} + b \]  

\( k \) takes 0.351 and \( b \) takes 0.73.

Determine the number of hydraulic transformers to be operated according to a given power value \( N \),

\[ m = [S_N/N_0]+1 \]  

\( N_0 \) is the rated power of the generator.

From (2) and (3), the flow rate value of the high pressure pool flowing into the turbine \( Q_2 \) can be obtained. The standard value of the flow of the piston hydraulic cylinder into the high pressure pool is:
The pressure of the water in the high-pressure pool is negligible, and the pressure of the high-pressure pool is the gas pressure in the pool, and its target value is:

$$P_2 = \frac{V - Sh_0}{V - Sh}$$  \hspace{1cm} (6)

Among them, $h$ is the height of the water surface in the high-pressure pool. The head caused by the difference between the height of the high-pressure pool and the low-pressure pool is very small, which can be neglected. The pressure of the high-pressure pool $P_2$ is approximately equal to the head $H$ of the turbine.

In order to stabilize the pressure of the high-pressure water tank at a given power, it is necessary to compensate for the change of the pressure of the high-pressure water tank. The compensation time is set to $T$. Within the compensation time $T$, the flow of the piston hydraulic cylinder into the high-pressure water tank is:

$$Q_t = Q_2 + \frac{S(h_2 - h_1)}{TQ_0}$$  \hspace{1cm} (7)

$h_2$ is the height of water surface after power regulation, $h_1$ is the height of water surface before power regulation, and $\Delta h$ is the change of water surface height in high pressure tank.

$$\Delta h = \int\frac{Q_0(Q_1 - Q_t)}{S}dt$$  \hspace{1cm} (8)

### 3.1.2. Power generation condition model

The output formula of the turbine is [9]:

$$N_t = 9.81HQ\eta \quad (\text{kW})$$  \hspace{1cm} (9)

It can be seen from Table 1 that the efficiency $\eta$ of the turbine operating condition is 86.52%, the maximum head of the turbine is 33.6 m, the minimum head is 21 m, and the design head is 31 m. For the convenience of calculation, the standard is expressed by the standard value, and the water head adjustment range is 0.677~1.084. The relationship between the turbine head and the output power is:

$$H = kN_t^{2/3} + b$$  \hspace{1cm} (10)

$k$ takes 0.407 and $b$ takes 0.677.

### 3.2. Strategy Principle and Process

Under different load requirements, the operating parameters of each module of the power station will change. According to the power adjustment command, the ideal parameters for stable and efficient operation of each module (such as head $H$, flow $Q$, average speed of hydraulic piston $v$, etc.) are obtained. At the same time, according to the calculation result, the driving equipment of the piston hydraulic cylinder is controlled and adjusted, so that the average flow rate of the inflow and outflow high pressure water pool is equal, and the compensation head reaches the ideal value, thereby realizing the rapid adjustment response of the power and the stable and efficient operation of the power station.
4. Simulation

The power $N$ in the initial state is 800 kW, and when $t=30$ s, the power command output power is 500 kW. The calculation results of the parameters before and after the power command are issued are shown in Table 4.

| Parameter | Power N (pu) | Head H (pu) | Flow $Q_2$ (pu) | Height h (m) | Average Speed $\bar{v}$ (m/s) | Number of Groups |
|-----------|-------------|-------------|-----------------|--------------|------------------|------------------|
| Before    | 0.8         | 1.033       | 0.662           | 2.094        | 0.408             | 4                |
| After     | 0.8         | 0.951       | 0.449           | 1.846        | 0.370             | 3                |

It can be seen from Table 4 that before the power adjustment, a total of four sets of hydraulic transformers are put into operation. The average running speed of each set of hydraulic piston rods is 0.408 m/s.

Figure 2. Operating speed of hydraulic piston rod. Figure 3. High pressure water pool height change.

After the power command is issued, that is, when $t=30$ s, a total of five sets of hydraulic transformers are put into operation. During the compensation time $T=3$ s, the driving equipment of each set of piston hydraulic cylinders is adjusted so that the average operating speed of the hydraulic piston rod is 0.174 m/s. When $t=33$ s, adjust the hydraulic cylinder drive equipment so that the average operating speed of the hydraulic piston rod is 0.37 m/s. Fig. 2 is the simulation diagram of the hydraulic piston rod speed of $t=0 \sim 60$ s. Fig. 3 is a simulation diagram of the height change of high-pressure water tank under power generation conditions. It can be seen that within $t=0 \sim 30$ s, the liquid level height fluctuates in the range of $(\pm 2\%)$ near 2.094 m. Within $t=30 \sim 33$ s, the height of liquid level decreases to 1.846 m, and then fluctuates in the range of $(\pm 2\%)$ near 1.846 m.

5. Conclusion

In this paper, the parameters of pumped storage power station are designed, and the power regulation strategies for stable operation of power generation and electric conditions are put forward. The ideal values of power plant parameters before and after power regulation under electric condition are calculated respectively, and the operation process of hydraulic piston is mathematically modeled and simulated. The running speed of the hydraulic piston rod in the range of 0-60 s and the height change of the liquid level in the high-pressure water tank are simulated. It is proved that the strategy is feasible, and the fluctuation of the head of the high-pressure pool is within $\pm 2\%$, which improves the operation efficiency of the power plant and makes the system run more stable.
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References
[1] Fu H , Jiang T, Cui Y, et al. Design and Operational Strategy Research for Temperature Control Systems of Isothermal Compressed Air Energy Storage Power Plants [J]. Journal of Thermal Science, 2019.
[2] You Jiayu, Jiang Tong. Design and operation strategy of pumped storage power station with virtual constant pressure pool capacity increase [J]. Hydroelectric Power, 2019, 45 (4): 79-83.
[3] Chen Jianhua, Meng Qingguo, Chen Zhenwu. Application status and development trend of variable frequency speed control unit in pumped storage power plant ([C]// Pumped Storage Power Station). 2010.
[4] Huang Shunli, Gexin. Progress of pumped storage unit variable speed technology [J]. Huazhong Electric Power, 2000, 13 (1): 68-69.
[5] Lung J K, Lu Y, Hung W L. Modeling and dynamic simulations of doubly fed adjustable-speed pumped storage units [J]. IEEE Transactions on Energy Conversion, 2007, 22 (2): 250-258.
[6] He Guoren, Zhou Siwu. Research on improving turbine efficiency by using Dual-Speed generators in hydropower stations with large head change [C]//Collection of Papers of the Nineteenth China Symposium on Hydropower Equipment. 2013.
[7] Zhang Qinghua, Ma Xiangfei. Summary of pumped storage generator units at Cuntangkou Hydropower Station [J]. Dong Fang Electric Review, 1994 (2): 82-85.
[8] Liu Zhuxi. Pumps and Pumping Stations [M]. Hydraulic and Electric Power Press, 1986.
[9] Huang Li, Li Xianshan, Yuan Xilai. Modular modeling and simulation of hydropower units based on simulink [J]. Hydropower Automation and Dam Monitoring, 2007 (5): 14-17.