Design and Operation Strategy for Pumped Storage Power Plant with Large Water Head Variation

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Abstract. The head of pumped storage power station is usually set in a small range. When the water head changes in a wide range, it will lead to the reduction of turbine power efficiency and the life of hydraulic turbines. However, the limit of the range of water head change will result in the waste of reservoir capacity and limit the daily power generation. In order to increase the variation of water head in the design of power station, a pumped storage power station using virtual constant pressure tank is proposed in this paper. The concept of hydraulic constant pressure network is introduced. A virtual constant pressure tank is used as a hydraulic accumulator in a hydraulic constant pressure network. A group of hydraulic cylinders with different area ratios are used as hydraulic transformers. The water head of the large change in the reservoir is transformed into the head of the small and medium range in the virtual constant pressure tank through the hydraulic transmission mechanism, and then the power and storage of the pump/water turbine will be carried out. It ensures the efficient operation of the turbine and increases the capacity of sustainable power generation.

1. Introduction
The head of pumped storage power station is usually set in a small range. When the change range of water head is large, the power generation efficiency of the turbine is reduced. The vibration of the turbine and the crack of the turbine runner blade will occur, and the safe and stable operation of the hydropower station will be affected by [1]. Therefore, the head of pumped storage power station should be set in a small range, but this will result in the waste of reservoir capacity. The upper reservoir of Xilongchi Pumped Storage Power Station has a normal storage level of 1492.5m, a dead water level of 1467m, a total storage capacity of $6.34.851 \times 10^6 m^3$ and a regulating storage capacity of $6.34.241 \times 10^6 m^3$. The lower reservoir has a normal storage level of 838m, a dead water level of 798m, a total storage capacity of $6.34.942 \times 10^6 m^3$ and a regulating storage capacity of $4.215 \times 10^6 m^3$ [2]. The capacity of the reservoir can’t be fully utilized and the sustainable generation capacity is reduced.

In order to cope with the large change of reservoir head of pumped storage power station, the frequency conversion speed regulation unit is adapted to different running heads by changing the speed. The frequency conversion AC excitation speed control unit was first put into commercial operation in Japan in 1990. Kazunogawa Pumped-storage Power Station in Japan is the largest storage power station with the largest capacity of variable frequency speed control unit in the world [3]. The variable frequency speed regulation unit can increase the range of water head and the range of power adaption.
reduce vibration, cavitation erosion and sediment abrasion, and improve the stability of the unit. However, the design of the device structure is more complex, and the maintenance cost of the AC excitation system of the transmission unit and the electric motor collector ring and the brush part should be maintained, and the maintenance cost is increased [4]. It will also reduce the efficiency of hydraulic turbines and greatly reduce the service life of hydraulic turbines.

Therefore, the concept of the hydraulic constant pressure network is introduced. A virtual constant pressure tank is used as a hydraulic accumulator in a hydraulic constant pressure network. A piston hydraulic cylinder with various areas of different area ratio is used as a hydraulic transformer in a hydraulic constant pressure network to realize variable pressure. A pumped storage power station which uses a virtual constant pressure pool is proposed. Through the joint action of the hydraulic transmission mechanism and the driving equipment, the water head of the large change in the reservoir is transformed into the water head of the small and medium range in the virtual constant pressure pool, and then the power generation and energy storage of the pump turbine is carried out. In this paper, a speed control strategy for driving equipment is put forward to further regulate the constant head of the virtual constant pressure tank, so as to ensure the efficient operation of the turbine.

2. Analysis of system principle

2.1. Hydraulic constant pressure network
The hydraulic constant pressure network system is a new type of hydraulic system developed in recent years. It has many advantages, such as high efficiency, simple structure and so on. A hydraulic constant pressure network system consists of energy source, hydraulic accumulator, high and low two driving oil roads and load [5].

A hydraulic accumulator is a pressure vessel for storing and releasing energy. It stores the pressure oil in the hydraulic system and is re-released when needed. In hydraulic constant pressure network system, hydraulic accumulators and hydraulic transformers are usually used in series, so that energy recovery can be carried out while maintaining constant pressure [6].

2.2. Hydraulic transformer
A hydraulic transformer is a hydraulic element that can be converted into pressure in a hydraulic transmission. It is equivalent to a pressure converter and can obtain energy from a hydraulic constant pressure network system without loss of throttle. Hydraulic transformer is divided into hydraulic cylinder type hydraulic transformer and hydraulic motor/pump type hydraulic transformer.

The hydraulic cylinder type hydraulic transformer is joined together by two single cylinder hydraulic cylinders. Because the effective area of the two sides of the piston is different, the pressure of the two sides of the oil is different, thus the pressure variable is realized.

The hydraulic motor/pump type hydraulic transformer is connected by the axial piston pump and the motor through a shaft, so that the two can rotate together and change the displacement of the variable motor by changing the two pumps/motors to use their own roles to do the pump or motor, and go into the two-way variable pressure [7].

If the hydraulic motor/pump type hydraulic transformer and hydraulic cylinder are used together, the power matching and energy utilization ratio can be realized. The variable cylinder is controlled by the electro-hydraulic servo valve or the electro-hydraulic proportional valve, and then the displacement of the transformer motor is adjusted to realize variable pressure. In practice, variable cylinders are integrated with hydraulic transformers [5].

2.3. Design of device structure
In this paper, the concept of hydraulic constant pressure network is introduced. A virtual constant pressure tank is used as a hydraulic accumulator in a hydraulic constant pressure network. A piston hydraulic cylinder with various areas of different area ratio is used as a hydraulic cylinder type hydraulic transformer in a hydraulic constant pressure network to realize variable pressure. A pumped storage
power station which uses a virtual constant pressure tank to cope with a large range of water head is proposed.

![Diagram of pumped storage power station with large variation of water head.](image)

**Figure 1.** Installation diagram of pumped storage power station with large variation of water head.

The structure of the power station is shown in Figure 1. The upper reservoir and the lower reservoir form the first potential energy. The virtual constant pressure pool and the low-pressure pool constitute the second potential energy. The hydraulic transmission mechanism is composed of a number of different groups of piston hydraulic cylinders with different area ratio, and the driving equipment is connected with the end of the piston rod in the hydraulic cylinder. According to the pressure change of the first potential energy and the second potential energy in the operation process, the hydraulic cylinder with different area ratio is chosen, so that the resultant force produced by the two groups of potential energy on the piston rod drives the piston rod movement. The movement speed and direction of the piston rod are controlled by the driving device. By setting the opening and closing of multiple valves in the hydraulic cylinder, power generation and energy storage can be realized [8].

### 2.4. Operation process

When the pumped storage power station is in the state of power generation, the hydraulic cylinder that selects the corresponding area ratio is selected according to formula (1). By controlling the opening and closing of the valve and pushing the piston rod into the reciprocating movement, the water flow into the hydraulic cylinder in the upper reservoir and then the hydraulic cylinder flow into the lower reservoir. The water in the low-pressure tank is pumped into the virtual constant pressure pool through the hydraulic cylinder, and then the water turbine is generated from the virtual constant pressure pool, and the power is sent to the power grid.

When the pumped storage power station is in the state of energy storage, the hydraulic cylinder with corresponding area ratio shall be selected according to the formula (1). The pump takes water in the low-pressure pool into the virtual constant pressure pool, and then flows into the hydraulic cylinder from the virtual constant pressure pool. By controlling the opening and closing of the valve, the piston rod is pushed back and forth, and the water in the lower reservoir is pumped into the upper reservoir.

In the process of power generation and energy storage operation of pumped storage power station, the water head constant in the virtual constant pressure cistern is realized by adjusting the driving device. The adoption of multi cylinder hydraulic transformer with different area ratio can reduce the loss in the process of operation, and the selection formula of the area ratio is:
\[ \frac{S_1}{S_2} = \frac{P_2}{P_1} \]  

Among them, \( P_1 \) is the pressure of the water in the reservoir, and \( P_2 \) is the pressure of the water in the virtual constant pressure tank, and it is a fixed value.

3. Speed control strategy of driving equipment

In the operation of pumped storage power station, in order to control the constant water head in the virtual constant pressure pool, the area ratio of the hydraulic cylinder must be determined first, and then the driving equipment is adjusted to control the flow velocity between the hydraulic cylinder and the virtual constant pressure pool. This paper presents a speed control strategy for driving equipment, called Equal Flow Rate and Water Head Compensation Control Strategy.

3.1. Principle of strategy

The principle of Equal Flow Rate and Water Head Compensation Control Strategy is to control the average flow velocity between the piston hydraulic cylinder and the virtual constant pressure pool equal to the average flow velocity between the virtual constant pressure pool and the hydraulic equipment. At the same time, the head change in the virtual constant pressure pool should be compensated to make it return to the standard value, thus ensuring the constant pressure in the virtual constant pressure tank.

3.2. Implementation of strategy

This paper sets different speed gear for driving equipment. Set the gear before each adjustment as the initial gear, and the speed change between adjacent speed gears is the same, as shown in Table 1.

| Table 1. Speed gear of driving equipment. |
|------------------------------------------|
| Speed down | Initial gear | Speed up |
| ⋯         | \( n_0 - 3 \) | \( n_0 - 2 \) | \( n_0 - 1 \) | \( n_0 \) | \( n_0 + 1 \) | \( n_0 + 2 \) | \( n_0 + 3 \) | ⋯ |

Figure 2 is the flow chart of Equal Flow Rate and Water Head Compensation Control Strategy. Monitor water head changes \( \Delta h \) in the virtual constant pressure tank at intervals of \( T_i \).

\[ \Delta h = h_2 - h_1 \]  

Calculate the velocity variation of water flow in liquid pipe between the virtual constant pressure tank and hydraulic equipment according to formula (3). The \( k \) in the formula is a constant.

\[ \Delta v_2 = \left| \frac{kpg\Delta h}{T_i} \right| \]  

The speed variation between the gears of the driving equipment is \( \Delta v \). Calculate the number of gears that the driver should adjust as formula (4).

\[ n_1 = \left\lceil \frac{\Delta v_2}{\Delta v} \right\rceil \]
Set compensation time as $T_2$. According to the change of water head based on standard water head $H_0$, the number of gears that need compensation is calculated as formula (5).

$$n_2 = \frac{k \rho g \left| H_0 - h_2 \right|}{T_2}$$

Then the actual number of gears that the drive device should adjust is $n_1'$:

$$n_1' = [n_1 + n_2]$$

When $|n_1| \geq 1$, the drive system starts up, otherwise it will continue to be monitored. Adjust the speed control gear to $n_0 + n_1'$, and after the speed control system start time $T_2$, restore the speed control gear to the gear $n_0 + n_1$.

![Flow chart of Equal Flow Rate and Water Head Compensation Control Strategy](image)

When the pumped storage power station is in the state of power generation, if the head of the virtual constant pressure pool is smaller than the standard head, that is, $h_2 < H_0$, the number of gears to be compensated is positive, otherwise it is negative. If the head of the virtual constant pressure pool drops during $T_1$ time, that is, $\Delta h < 0$, the number of initial gears that the drive device should adjust $n_1$ is positive, otherwise it takes a negative value.

When the pumped storage power station is in the state of energy storage, if the head of the virtual constant pressure pool is smaller than the standard head, that is, $h_2 < H_0$, the number of gears to be compensated is negative, otherwise it is positive. If the head of the virtual constant pressure pool drops during $T_1$ time, that is, $\Delta h < 0$, the number of initial gears that the drive device should adjust $n_1$ is negative, otherwise it takes a positive value.
3.3. Speed control system
The control part of the driving device is composed of acquisition unit, strategy application unit and execution unit. The acquisition unit passes the water head signal in the virtual constant pressure tank to the strategy application unit through sensors. The strategy application unit can be analyzed and calculated by PLC or CPU control device. Then it is transmitted to the execution unit, and the execution unit can use the frequency converter to adjust the driving device, which can use a linear motor.

4. Conclusion
Compared with the traditional pumped storage power station, the pumped storage power station with virtual constant pressure pool has the following advantages:

1) It can adapt to a wider range of head changes, make full use of reservoir capacity, and reduce the environmental requirements for pumped storage power station construction.

2) It can ensure the efficient and stable operation of the turbine and increase the service life of the turbine.

3) The structure design of the device is simple, and the hydraulic transmission mechanism in the experimental device is composed of several groups of piston hydraulic cylinders with different area ratio, which is convenient for design and manufacture.

The speed control strategy of driving equipment can make the head of virtual constant pressure tank fluctuate near the standard water head, which ensures the power generation efficiency of the turbine. The restriction of turbine head is no longer the limiting factor of the head of reservoir and the amount of sustainable power generation increased. At the same time, the environmental requirements for the construction of pumped storage power stations are reduced. The application scope is expanded, and better popularization is achieved.

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