Real machine Test inversion research of J Pumped Storage Power Station

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Abstract: Accurate prediction of transition process is an important issue in the design and operation of pumped storage power station. In this paper, combined with load rejection test of J Pumped-storage Power Station, the basic equation of water flow motion and the element matrix equation of the turbine were established first, and the calculation model was established through HYSIM software. Then for the 100% load rejection control condition, the inversion calculation and analysis of actual load rejection test under the same boundary condition were carried out. According to the comparison process line between numerical simulation and measured data of the surge-chamber water level, a comprehensive combination calculation was used to calibrate the impedance coefficient of surge-chamber. Finally, based on the calibrated impedance coefficient, a new calculation model was established, and the inversion calculation was carried out again. By comparing the numerical simulation and measured data of volute and tail pipe pressure, the pressure pulsation characteristics of the characteristic parameters of the unit were obtained, and the correction value of pressure pulsation was obtained. The calibration method and pressure pulsation correction method adopted in this paper can provide a reference for the inversion analysis of load rejection test in similar power stations.

1. Introduction
J Pumped Storage Power has an installed capacity of 1,800MW, an average annual power generation of 3.015 billion kW·h, and an annual pumping power consumption of 4.02 billion kW·h. The power station is equipped with 6 vertical-shaft single-stage Francis water pump turbine-generator motor units with a single unit capacity of 300MW. The power station is connected to the East China Power Grid at a voltage level of 500kV, and is responsible for peak regulation, valley filling, frequency regulation, phase modulation, black start and accident backup in the system.

The pivot building is mainly composed of upper reservoir, lower reservoir, water delivery system, underground powerhouse, switch station and central control building. The upper and lower reservoirs are all concrete face rockfill dams. The total length of the water delivery system is about 2809.1m, of which the length of the water diversion system is about 1766.8m, and the length of the tailrace system is about 1042.3m. The water diversion system adopts the "three holes and six machines" inclined shaft layout, and the water diversion surge chamber is arranged at the end of the diversion tunnel, and adopts the impedance + upper chamber structure. The tail water system adopts the layout of "one hole and two machines". The tail water surge chamber is located 20m downstream of the tail water bifurcated pipe and adopts impedance + upper chamber structure.
2. Mathematical model

2.3. The basic equation of water flow

The calculation method for the elements of a pressurized elastic pipeline adopts the most commonly used calculation method for unsteady unsteady flow——the characteristic line method\(^{[1-3]}\). The transient flow flowing through the closed pipeline is described by the equation of motion and the continuous equation, as follows:

\[
\frac{\partial Q}{\partial t} + gA \frac{\partial H}{\partial x} + \frac{f}{2DA} Q|Q| = 0
\]

(1)

\[
\frac{a^2}{gA} \frac{\partial Q}{\partial x} + \frac{\partial H}{\partial t} = 0
\]

(2)

In the formula, \(Q\) is the flow rate of the pipe, m/s\(^3\); \(H\) is the pressure head, m; \(x\) is the length along the pipe axis; \(D\) is the pipe diameter, m; \(A\) is the pipe area, m\(^2\); \(t\) is the time variable, s; \(a\) is the water hammer wave velocity, m/s; \(g\) is the acceleration of gravity, m/s\(^2\); \(f\) is the friction coefficient; \(\alpha\) is the angle between the pipe axis and the horizontal plane.

2.3. Matrix equation of hydraulic turbine elements

The head and flow rate of a certain known state point of the pump-turbine are represented by \(H_0\) and \(Q_0\) respectively, which can be approximated by Newton one time to another state point that is close to the known state point and are connected by the following equation:

\[
H = H_0 + \frac{dH}{dQ}(Q - Q_0)
\]

(3)

Can be simplified to:

\[
H = H_0 + Z_0(Q - Q_0)
\]

(4)

Where is the hydraulic resistance of the pump turbine when the head is and the flow is.

![Figure 1. End-point state variables and flow direction of the turbine](image)

The calculation and analysis software used in this paper is the Hysim program self-developed by the East China Institute. Aiming at the pipeline layout of the water delivery system, the established
calculation model is shown in Figure 2, and the corresponding pipeline parameters are shown in Tab1.

![Figure 2. Calculation model](image)

**Table 1. Pipeline parameter table of water transmission and power generation system**

| Pipe number | Length (m) | Area (m) | Hydraulic radius (m) | Local loss coefficient | Remarks          |
|-------------|------------|----------|----------------------|-----------------------|------------------|
| L1          | 97.15      | 61.94    | 0.590                | 0                     | Concrete lining  |
| L2          | 526.96     | 28.27    | 1.50                 | 0.2800                | Concrete lining  |
| L3          | 54.42      | 27.43    | 1.420                | 0.1400                | Concrete lining  |
| L4          | 1018.58    | 16.41    | 1.110                | 1.3000                | Steel lining     |
| L5          | 72.10      | 5.72     | 0.550                | 0.2200                | Steel lining     |
| L6          | 108.00     | 15.21    | 1.080                | 0.2500                | Steel lining     |
| L7          | 26.15      | 26.4     | 1.170                | 0.5000                | Concrete lining  |
| L8          | 65.86      | 5.68     | 0.540                | 0.1800                | Steel lining     |
| L9          | 105.00     | 15.21    | 1.080                | 0.2500                | Steel lining     |
| L10         | 38.49      | 22.81    | 0.960                | 0.5000                | Concrete lining  |
| L11         | 20.00      | 1.50     | 28.27                | 0                     | Concrete lining  |
| L12         | 746.19     | 1.50     | 28.27                | 0.1000                | Concrete lining  |
| L13         | 123.75     | 54.69    | 0.650                | 0.8800                | Concrete lining  |

Note: (1) The head loss coefficients of power generation and pumping parts and bifurcated pipes are all in accordance with $\zeta = \frac{Q^2}{2gA^2}$.

(2) The roughness of the reinforced concrete section of the water diversion and tail water is selected according to the average value of 0.014, and the roughness of the steel lining section is selected according to the average value of 0.012, and the volute and draft tube section are not counted because their head loss is included in the efficiency of the turbine. Its head loss, roughness is taken as 0.

### 3. Guide vane closing rule

The hydraulic turbine operating conditions of the power station adopt a two-segment closing rule of slow and fast closing. The total time $T_1$ of the first period of closing rule is 92s, the inflection point is 65%, and the total time of the second period of closing rule $T_2$ is 32s; The total time for the guide vane to close from the rated opening to 0 opening is about 38.7s. The guide vane closing rule used in this project is shown in Figure 3.
4. Field load rejection test and back analysis

4.1. Description of working conditions
This article mainly focuses on the comparative analysis between the single unit load rejection test and calculation simulation of 1# and 2# units. The test conditions are as follows:

Test1 condition: the upper reservoir water level is 933.10 m, the lower reservoir water level is 333.20 m, 2# unit shuts down, 1# unit carries 100% (300 MW) load, suddenly full load, and the unit guide vanes are normally closed;

Test2 condition: the upper reservoir water level is 944.10 m, the lower reservoir water level is 331.10 m, unit 1 is shut down, unit 2 is 100% (300 MW) load, suddenly full load, and the unit guide vanes are normally closed.

The parameters measured in the test include the unit's active power, guide vane opening, speed, main shaft swing, unit vibration and water pressure pulsation, etc. This article mainly focuses on surge fluctuations in the surge tank, volute and draft tube when the unit is unloaded. The pressure and pressure pulsation are compared with numerical simulation for verification.

4.2. Rated impedance coefficient
The Hysim transition process calculation software is used to perform inversion calculations on the above working conditions, and the calculated value of surge water level in the surge tank is compared with the measured value, as shown in Table 2.

Table 2. Summary table of calculation and actual measurement of water level in surge tank under test conditions

| Location                        | Measured extreme value (m) | Calculate extreme values (m) | Head difference (m) | Water level monitor elevation (m) |
|---------------------------------|-----------------------------|-----------------------------|---------------------|---------------------------------|
| Water diversion and pressure regulation | 937.09/927.77 | 935.68/929.03 | 1.41/1.26 | 901 |
| Tail water surge chamber         | 342.33/329.27 | 341.12/330.16 | 1.21/0.89 | 300 |

By analyzing the data of the adjustment and tail adjustment, it is found that under the 100% load rejection condition, the error of the initial water level elevation of the adjustment is 1.3m, and the initial water level elevation difference of the tail adjustment is 3.3m. The loss rate is fixed, and the initial water level is basically the same, but the swell extreme value still has a certain deviation. Through analysis, the main reason for this deviation is that the value of the impedance coefficient of the surge chamber is inconsistent with the actual value. It needs to be re-calibrated on the basis of the impedance hole coefficient of the model surge chamber.

The head loss coefficient of the impedance orifice can be calculated approximately according to the
formula, and the discharge coefficient of the impedance orifice can be obtained by experiment, and can be selected between 0.60 ~0.80 in the preliminary calculation; the impedance coefficient of the surge chamber is, and s is the discharge coefficient.

4.2.1. Determination of impedance coefficient of water diversion surge tank
The comparison between the numerical calculation of the water level process line of the diversion surge tank and the field test is shown in Figure 4. From the comparison process line, the fluctuation range and the extreme value of the surge calculation of the diversion surge tank are smaller than the actual measured value, and the extreme value differs by 1.6m. The analysis reason is that the impedance coefficient of the calculation model is inconsistent with the actual situation. After the impedance coefficient calibration, the inflow impedance coefficient of the model diversion surge tank was changed from the original 2.778 to 1.563, and the outflow impedance coefficient was revised from the original 1.563 to 1.235. The calculated surge fluctuation amplitude and extreme value are more consistent with the actual measurement results. In order to be close, the process line is also more fitting.

4.2.2. Determination of impedance coefficient of tail water surge tank
The comparison between the numerical calculation of the water level process line of the tail water surge tank and the field test is shown in Figure 5. From the comparison process line, the fluctuation range and extreme value of the tail water surge tank surge calculation are smaller than the actual measured value, and the extreme value differs by 1.0m. The analysis reason is that the impedance coefficient of the calculation model is inconsistent with the actual situation. After the impedance coefficient calibration, the inflow impedance coefficient of the model diversion surge tank was changed from 2.778 to 2.041, and the outflow impedance coefficient was corrected from the original 1.563 to 1.235. The calculated surge fluctuation amplitude and extreme value are more consistent with the actual measurement results. In order to be close, the process line is also more fitting.
4.2.3. Summary
After evaluating the influence of the elevation of the measuring point and the water loss, the study found that there is still a certain error between the extreme water level of the surge tank and the actual measurement result. The reason is that the value of the impedance coefficient of the surge tank in the numerical calculation is deviated from the actual situation. Therefore, the impedance coefficient needs to be calibrated.

After analysis and comparison, it is finally determined that the inflow/outflow impedance coefficient of the impedance adjustment hole adopts 1.563/1.235, and the inflow/outflow impedance coefficient of the tail adjustment impedance hole adopts 2.041/1.235. The impedance coefficient of the surge chamber recommended in the specification is 1.563–2.778. Affected by factors such as the accuracy of the measuring instrument, there is a certain error in the calibration of the impedance coefficient. Generally speaking, the calibration result does not deviate much from the specification range. The results of this calibration provide a reference and basis for the calculation of surge surge in impedance surge chamber and the value of impedance coefficient in the future.

4.3. Inversion prediction analysis
According to the results of the impedance coefficient calibration, the calculation model is re-established, and the calculation is carried out under the same conditions for the 1# and 2# single unit load rejection test conditions, and the maximum pressure at the inlet of the volute, the minimum pressure at the draft tube inlet, and the extreme value of the rate of increase of the unit speed are analyzed. The specific inversion calculated values and the comparison with the actual measured values are shown in Tables 3 and Figures 6 to 11.

Table 3. Summary Table of Relative Differences between Unit Load Rejection and Pumping and Power-off Conditions

| Controlparameters                     | 1# measured value | 1# calculated value | 1# relative difference (%) | 2# measured value | 2# calculated value | 2# relative difference (%) |
|--------------------------------------|-------------------|---------------------|----------------------------|-------------------|---------------------|----------------------------|
| Maximum pressure of volute inlet (m) | 898.00            | 855.67              | -7.1404                    | 806.85            | 793.78              | -2.1424                    |
| Minimum pressure of draft tube inlet (m) | 57.28            | 69.74               | 2.1018                     | 24.33             | 66.14               | 6.9112                     |
| Maximum speed increase rate          | 34.7              | 33.97               | -0.73                      | 35.01             | 35.52               | 0.51                       |

Note: Relative difference = (calculated value - measured value)/net head

Figure 6. Test1 condition 1# unit volute inlet pressurcalculation and measured waveform diagram
Figure 7. Test1 condition 1# unit draft tube inlet pressurcalculation and measured waveform diagram
The comparison and analysis of calculation and experiment from the chart show that:

(1) There is a certain deviation between the calculated extreme value and the measured extreme value, which is mainly manifested as:

   (1) The maximum pressure at the inlet of the volute, for the 1# unit, the difference between the calculated extreme value and the measured extreme value is -42.33m (the relative net head is -7.14%); For the 2# unit, the difference between the calculated extreme value and the measured extreme value is -13.073m (the relative net head is -2.14%). The larger value -7.14% can be used as the pressure pulsation correction.

   (2) The minimum pressure at the draft tube inlet, for unit #1, the difference between the calculated extreme value and the measured extreme value is 12.46m (the relative net head is 2.10%); For unit 2#, the difference between the calculated extreme value and the measured extreme value is 41.81m (the relative net head is 6.91%). The maximum value of 6.91% can be used as the pressure pulsation correction.

   (3) The maximum rise rate of the unit's speed, the calculated extreme value and the measured extreme value are small, so no correction is needed.

(2) Under each test condition, the measured wave pattern of the unit speed rise rate, the inlet pressure of the volute and the inlet pressure of the draft tube are basically consistent with the calculated fluctuation curve. The occurrence time area of the measured extreme value is basically the same as the occurrence time area of the calculated extreme value, and the measured average value is in good agreement with the calculated average value.

5. Conclusion
Based on the on-site load rejection test of J Pumped-storage Power Station, this paper uses Hysim calculation software to compare the actual measurement results and numerical simulation calculations, the rated value of the impedance coefficient of the surge tank is rated, and the correction value produced
by the influence of pressure pulsation and calculation error is studied. The conclusion shows:

1. There is a deviation between the model test value of the surge tank impedance coefficient and the prototype measured value. In the calculation and analysis of the transition process, attention should be paid to the impedance coefficient sensitivity analysis, and a certain elevation margin should be considered in the structural design.

2. The measured data and the numerical simulation calculation results are more consistent with the law from the process line, and the extreme value has a certain deviation, mainly because the measured pressure contains the cause of pressure pulsation.

3. The results of this calculation and calibration provide a reference for the calculation of impedance surge chamber surge and the value of impedance coefficient in the future, and provide a basis for the safe and stable operation of the power station.

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