Inversion calculation and prediction of extreme conditions by in-situ test of real machine in a hydropower station

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Abstract. The in-situ test of the real engine in hydropower station is a necessary test before the unit is put into operation. During the test, the problems in the test process can be found through the auxiliary inversion calculation, and the calculation and analysis of extreme conditions can provide important support for the unit's permanent operation. First of all, this paper analyzes the problem that the maximum pressure of the spiral shell and the increase rate of the unit speed in the load rejection test of the hydropower station exceed the control standard. Through inversion calculation, it is found that the closing law of the guide vane of the unit is different from the set closing law, and the robustness of the closing law is poor; then, combined with the test situation, the closing law of the guide vane of the unit was optimized. While the adjusted load rejection test was simulated under the same boundary conditions, and the measured data and numerical calculation results were compared and analyzed to obtain the modified values of the characteristic parameters. Finally, the extreme conditions in the transition process of large fluctuations are predicted and calculated by numerical simulation. This research idea provides reference and guidance experience for similar projects.

1. Project Overview
A power station was originally designed to install two hydro turbine generators with a single capacity of 50MW, with a total installed capacity of 100MW. In order to improve the efficiency of power generation and water utilization, the third unit was expanded. Its water diversion system is composed of bank-slope water inlets, diversion tunnels, penstocks and other buildings. The total length of the water diversion system from the water inlet to the center line of the unit is 514.817m. The water diversion power generation system is located on the left bank, the inlet is located on the downstream side of the gully about 160m upstream of the dam, and the site is located at the gully about 300m downstream of the dam axis. A single-unit 100MW hydro-generator unit is installed with a single-tube single-unit arrangement.

2. The optimizing adjustment of closing law
In the first 100% load rejection test, the guide vanes of the unit adopted a 13-second linear closing law. During the test, the maximum increase rate of the unit's speed reached 57.36%, exceeding the 55% control standard; The actual maximum pressure of the spiral shell has reached 112m water column, exceeding the control standard of 106m water column, as shown in Figures 1 and 2. Through the analysis of the load rejection process line and the inversion calculation of the test conditions, as shown in Figures 3 to 4, it is found that the sudden increase in the slope of the back section of the closing law process line
is the direct cause of the rapid rise of the spiral shell pressure and speed. The reason for the change in the closing law is that the rate of increase in speed exceeds the set value of the unit. According to the results of the inversion calculation, the maximum rate of increase of the unit's speed is 55.22% under this closing law, which has exceeded the control value. It can be seen that the use of such a closing law is detrimental to the safety of the power station.
It can be seen from the characteristic curves of unit flow, torque and speed in Figures 5–6 that when the unit is unloaded, with the closing of the guide vanes, the flow decreases, and positive water hammer occurs in the pipeline [1] while the turbine head increases; With the closing of the guide vanes, the unit torque gradually decreases, but the unit speed continues to increase. In order to balance the contradiction between the decrease of water hammer pressure and the increase of unit speed, the closing law of guide vane of unit was optimized and calculated.

From the perspective of the calculation and analysis of the transient process, the optimization of the guide vane closing law mainly affects the maximum pressure at the inlet of the spiral shell, the minimum pressure at the inlet of the draft tube, and the maximum speed increase rate of the unit. For this power station, due to the short draft tube length, it is easier to meet the control requirements, so only the maximum pressure at the spiral shell inlet and the maximum speed rise rate of the unit are calculated and analyzed. Through the comprehensive analysis and calculation of various possible and reasonable control conditions, the T1 and T2 operating conditions are finally selected as the representative operating conditions for the optimization of the closing law, as shown in Table 1.

![Figure 5. Characteristic curve of unit flow and speed.](image1)
![Figure 6. Characteristic curve of unit torque and speed.](image2)

| Table 1. Representative working condition. |
|-------------------------------------------|
| Condition | Upstream water level (m) | Downstream water level (m) | Description of water level combination and load change |
|-----------|--------------------------|-----------------------------|------------------------------------------------------|
| T1        | 275.00                   | 209.19                      | Normal storage level of upper storeroom, lowest tailwater level of downstream, load rejection in accident |
| T2        | 271.20                   | 211.69                      | Three downstream machines at full power level, rated water head, unit rated output, load rejection in accident |

According to the selected two representative working conditions, a straight line of 9s, 10s, 11s, and 12s is selected for calculation. The calculation results of the optimization of the closing law are shown in Table 2.
Table 2. Calculation results of optimization of closing law.

| Closing law | T1  | T2  |
|-------------|-----|-----|
| Maximum pressure of spiral shell inlet (m) | Maximum speed increase rate of unit (%) |
| 9s          | 104.58 | 49.6 |
| 10s         | 100.89 | 51.2 |
| 11s         | 96.38  | 52.5 |
| 12s         | 93.72  | 53.7 |
| Control value | 106  | 55%  |

Through the above analysis, it can be seen that when the unit is closed in a straight line of 9s, 10s, 11s, and 12s, the maximum pressure at the inlet of the spiral shell and the maximum speed increase rate of the unit can meet the control requirements. As the guide vane closing time increases, the maximum pressure at the inlet of the spiral shell decreases, but the maximum increase rate of the speed increases. To ensure that there is a certain margin for the two control parameters, a 10s linear closing law is finally adopted, as shown in the figure 7.

3. Comparison and analysis of load rejection condition test and numerical calculation results

3.1. Load rejection test conditions and instructions

In order to test the safety and stability of the unit during the transition process of large fluctuations, to ensure that the pressure of the spiral shell and the speed of the unit during the load rejection process meet the requirements of the adjustment guarantee design value (because the tail water is short, it is easy to meet the control requirements, and the draft tube inlet is the smallest Pressure does not need to be discussed) [2~3], the hydropower station conducted the second load dump test on site of Unit 3#. The load rejection test conditions are shown in Table 3.
Table 3. Load rejection test conditions of 3# unit.

| Unit         | Tested projects | Upper reservoir water level (m) | Lower reservoir water level (m) | Change of load | Description of load variation                        |
|--------------|-----------------|--------------------------------|--------------------------------|---------------|------------------------------------------------------|
| 3#           | Single machine loads rejection 75% | 274.05                          | 210.45                          | 1 set → 0     | 3# unit operates normally with 75% load, the unit rejects all load, and the guide vanes are normally closed |
|              | Single machine loads rejection 100% | 274.04                          | 210.76                          | 1 set → 0     | 3# unit runs normally with 100% load, the unit rejects all load, and the guide vanes are normally closed |

According to the load rejection test, the numerical inversion calculation of the same working condition is carried out, and the measured data and the numerical calculation results are compared and analyzed to verify the accuracy of the numerical calculation. If the numerical calculations are in good agreement with the measured data, numerical simulation methods can be used to predict and calculate large fluctuations and extreme control conditions to provide a basis for the safe and stable operation of the power station.

3.2. Comparative analysis of measured results and numerical simulation calculation results

According to the test conditions, the simulation calculation of the large fluctuation transition process under the same boundary conditions is carried out. The measured and calculated values of the control parameters are shown in Tables 4 to 5. The comparison between the actual measurement process line and the calculation process line of each control parameter is shown in Figure 7~10.

Table 4. Comparison between actual measurement and numerical calculation of maximum pressure of spiral shell.

| Unit         | Tested projects | Measured values (m) | Calculated values (m) | Relative difference (%) |
|--------------|-----------------|---------------------|-----------------------|-------------------------|
| 3#           | Single machine loads rejection 75% | 94.33               | 98.47                 | 6.60                    |
|              | Single machine loads rejection 100% | 98.78               | 98.18                 | -0.97                   |

Table 5. Comparison between actual measurement and numerical calculation of maximum speed rise rate.

| Unit         | Tested projects | Measured values (m) | Calculated values(m) | Relative difference (%) |
|--------------|-----------------|---------------------|----------------------|-------------------------|
| 3#           | Single machine load rejection 75% | 26.83               | 25.32                | -1.51                   |
|              | Single machine load rejection 100% | 46.51               | 44.47                | -2.04                   |
**Notation.** The maximum pressure corrected value of the spiral shell of the unit is determined by "relative difference = (calculated value-measured value) / net water head before throwing"; the corrected value of the rate of increase of the rotation speed of the unit is determined by "calculated value-experimental value".

**Figure 8.** Comparison of measured and calculated process lines of spiral shell pressure with 75% load rejection.

**Figure 9.** Comparison between measured speed and calculated process line of 75% load rejection unit.

**Figure 10.** Comparison of measured and calculated process lines of spiral shell pressure with 100% load rejection.

**Figure 11.** Comparison between measured speed and calculated process line of 100% load rejection unit.

It can be seen from Table 2~3 and Figure 8~11 that the measured value is close to the extreme value of numerical calculation, and the process line rule of the numerical calculation is basically consistent with the measured result, and the numerical analysis result is in good agreement with the experimental measurement.

### 3.3. The modified value

In order to ensure the safety of the unit operation, corrections are made in accordance with the most unfavorable conditions of the existing real machine test conditions, and the maximum relative deviation is taken as the modified value. The specific modified value are shown in Table 6.
Table 6. Comparison of measurement and calculation of control parameters.

| Control parameters          | Measured values (m) | Calculated values (m) | Relative difference (%) | Conditions                                      |
|----------------------------|---------------------|-----------------------|-------------------------|-------------------------------------------------|
| Maximum pressure of        | 98.78               | 98.18                 | -0.97                   | 3# machine rejects 100% load                    |
|   spiral shell inlet       |                     |                       |                         |                                                 |
| Maximum speed increase     | 46.51%              | 44.47%                | -2.04                   | 3# machine rejects 100% load                    |
|   rate                    |                     |                       |                         |                                                 |

4. Recheck calculation and analysis of extreme control conditions

4.1. Extreme control conditions and instructions
Through comprehensive analysis and calculation of various possible and reasonable control conditions (considering the superposition of two accidental events), the T1 and T2 operating conditions, which control the maximum pressure at the inlet of the spiral shell and the maximum rate of increase in speed, are finally selected as the extreme control conditions. The control conditions are shown in Table 1.

4.2. Analysis of calculated results
Through the comparative analysis of the actual tested conditions and the numerical simulation, the calculated values of the various operating conditions of the large fluctuation transition process are corrected, and the correction value takes the maximum relative deviation in Table 4. The calculation results of extreme control conditions are shown in Table 7.

Table 7. Calculation and corrected results of characteristic parameters of control conditions.

| Conditions | Maximum pressure of spiral shell inlet (m) | Maximum speed increase rate (%) |
|------------|-------------------------------------------|---------------------------------|
|            | Measured values                          | Calculated values               | Measured values | Calculated values |
| T1         | 100.89                                    | 101.52                          | 40.8            | 42.84             |
| T2         | 93.48                                     | 94.04                           | 51.2            | 53.24             |

From the calculated results in Table 6, it can be seen that after parameter correction, the maximum pressure at the end of the spiral shell is 101.52m, which occurs in T1 working condition; the maximum increase rate of unit speed is 53.24%, which occurs in T2 working condition. The maximum pressure at the end of the spiral shell is designed to be 106m, and the maximum allowable rate of rise of the unit's speed is 55%. The revised parameters still meet the design control requirements.

5. Conclusion
The inversion calculation of the in-situ test of the hydropower station has great reference and guidance significance for the test. The inversion calculation can reveal some problems in the test process, and then through adjustment and optimization, it plays a very important role in ensuring the safety of the project. The inversion calculation under the same boundary conditions is carried out for the tested conditions. The calculation shows that the characteristic parameters can meet the design control requirements under the extreme control conditions. This inversion and prediction calculation method can predict working conditions that cannot be tested, ensure the safety of the project, and provide guidance experience for similar projects in the future.
References

[1] Zhu, M.L., Shen, B., Zhang, Y.H., Wang, T. (2007) Research on Water Hammer Protection of Long-distance Pressure Water Delivery Project. Journal of Xi'an University of Architecture & Technology, (01):40-43.

[2] Li, D., (2007) Comprehensive analysis of stability of Gongzui Hydropower Station Unit 3 after renovation. Hydropower and New Energy, Hydropower and New Energy, 32(09):48-52.

[3] Ge, X., Zhang, H., Lan, S.S., Huang, Z.C., Yang, C., Zhang, J.X. (2018) Analysis on hydraulic transition process of Jiaomutang Hydropower Station. Sichuan Water Resources Sichuan Water Resources, 39(06):10-12.

[4] Li, G.H., Yu, X.S. (2015) Analysis of load rejection test and simulation calculation results of a pumped storage power station. Yangtze River, 46(05):102-104+108.