Transient Process inversion calculation and extreme condition prediction of large pump turbine based on field test

Gaohui Li¹, Tianchi Zhou¹*, Xuesong Yu¹ and Minjie Yao¹

¹ Huadong Engineering Corporation Limited, POWERCHINA, Hangzhou, Zhejiang, 310000, China
*Corresponding author’s e-mail: 981416334@qq.com

Abstract. An innovative closing law, blocked for a while and then one segment linear closing, was investigated in a pump storage power station. It can mitigate the maximum pressure of the spiral case and the minimum pressure of the draft tube during load rejection. Problems also exist such as long load rejection process, intense unit vibration, large amplitude of the fluctuating pressure, large noise in the field. Considering the fluctuating pressure is significant in pump turbine, segmental correction method was proposed in order to guarantee the pressure inversion accurate. Field test under load rejection and hydraulic disturbance condition were conducted, proving that the fluctuating pressure is larger. The changing law of the fluctuating pressure was also obtained. The numerical result under the same condition agreed well with the test value, verifying the reliability of the numerical calculation. Numerical calculation was analysed under the extreme condition which is not suitable for field test. The result was corrected and then compared with the design value, checking the safety of the water conveyance system. The study provides reference for other pump storage power station.

1. Introduction

The pump storage power station in Fujian China has four 300 MW reversible pump turbines, whose total installed capacity is 1200 MW. The maximum net head of the turbine is 447.0 m. The whole water conveyance system is 2061.8 m in length. It is mainly composed of upper reservoir inlet/outlet, headrace tunnel, headrace bifurcated pipe, penstocks, tailrace branch pipe, tailrace bifurcated pipe, tailrace surge tank, tailrace tunnel and lower reservoir inlet/outlet. The station adopts the layout of one tunnel with two units. Namely, every two units are installed in one water conveyance system, sharing one common headrace and tailrace tunnel.

For pump storage power station, load rejection is a frequent occurrence because of power failure, device malfunction, or other accident. It is one of the key factors that affect the safe and table operation. During load rejection, wicket gate (WG) close rapidly in order to control the rotating speed of the turbine. As a result, the instability of the flow increases, leading to strong water hammer and fluctuating pressure, which is very dangerous to the system [1]. Most of the accidents happened in this process according to operation experience [2].

In the case of one tunnel with multiple units, once one turbine rejects the load or greatly increases the load, the rest will be affected in aspect of head and output, which will affect the power grid. This phenomenon is called hydraulic disturbance. For this station with large capacity and long diversion tunnel, the phenomenon is significant theoretically. There are three operation modes in the analysis of hydraulic disturbance: power regulation in ideal large power grid (ILPG), frequency regulation in ILPG and isolated frequency regulation.
Many experimental and numerical studies on hydraulic transients in hydropower systems have been conducted. Seleklı compared the numerical calculation results of transient pressures with field test data for the Catalan power plant in Turkey, and the agreement is satisfactory [3]. In Shahe pump storage power station, comparison of numerical results and test data were studied [4]. You compared the numerical calculations with field tests, studying the load rejection transient in Tianhuangping Power Plant, which is installed with misaligned guide vanes [5]. Wang studied the effect of wicket opening time on the transient process in hydropower station by theoretical analysis and numerical calculations [6]. Yu analysed the influence of successive load rejection conditions on water hammer pressure of spiral case based on the method of characteristics [7].

In this study, a novel closing law wherein the WG is blocked for 10s and then shut down with the slope 1/25 was presented. It can mitigate the maximum pressure in the spiral case \( H_{\text{max,s}} \) and the minimum pressure in the draft tube \( H_{\text{min,d}} \). Filed tests were conducted under load rejection and hydraulic disturbance conditions. The numerical results under the same conditions were compared with the test values, verifying the simulation software accurate. Calculation error of pressure, speed and output were also obtained from the comparison. Based on that, the numerical result under extreme condition was calculated and then corrected to examine the safety of the station.

2. Closing Law of Wicket Gate

The closing law of the pump turbine in this station is: the WG is blocked in the initial position for 10s and then shut down with the slope 1/25 when load rejection happens in generating condition, as shown in Figure 1; the WG is shut down with the slope 1/20 in pumping condition.

Since the water diversion system of the pump storage power station is long and narrow, the runner diameter of the reversible turbine is generally 30% to 50% larger than that of conventional turbine. The centrifugal force in reversible turbine is usually larger. Even in generating condition, there exists considerable centrifugal force, preventing water into the turbine. When the rotating speed reaches runaway speed, the centrifugal force increases sharply. At this time, even the rotation speed and servomotor stroke change a little, the flow changes greatly, resulting in huge water hammer pressure.

According to this characteristic, when load rejection happens, the WG is blocked so its opening stays the same. The rotating speed rises rapidly and the operating point approximates to the runaway line, near the “S” area, where turbine speed has increasing influence on flow change. During the blocked time, the change of flow is only caused by the increase of turbine speed, so the water hammer pressure is relatively small. When the pressure in the spiral case decreases, the WG is closed quickly to cut down the flow. Due to the rise of the speed, the flow is very small, so the WG closing will not lead to lager water hammer pressure.

In this station, the “S” area is steep and the effect of “flow interception” is significant [8], as shown in Figure 2. This type of closing law can reduce the maximum pressure of the spiral case to a certain extent.
3. Test Condition and Control Criterion

Field tests for this station were conducted under those conditions: two units using one tunnel reject load simultaneously (double units load rejection); one unit operates normally while the other rejects load (hydraulic disturbance). The key point of the former is the $H_{\text{max,s}}$, the $H_{\text{min,d}}$ and the maximum rotating speed of the turbine ($n_{\text{max,t}}$), while that of the latter is the maximum output of the normal operating unit ($N_{\text{max,u}}$).

3.1. Double Units Load Rejection Test

There are many load rejection field tests for pump storage power station. It can be known that, in condition of one water diversion system with two units, double units load rejection is much worse than single unit load rejection in terms of pressure and speed. The test conditions of double units load rejection are as follows.

Condition of test 1: the upstream water level is 728.90 m and the downstream water level is 287.17 m. Double units with 75% (225 MW) loads reject load simultaneously, and the WG closed normally.

Condition of test 2: the upstream water level is 730.25 m and the downstream water level is 287.23 m. Double units with 100% (300 MW) loads reject load simultaneously, and the WG closed normally.

To meet the safety requirements of the water diversion system and turbine, the main control criteria for guaranteed regulation calculation of the station are shown in Table 1.

| Characteristic parameter | Control criteria |
|--------------------------|------------------|
| $H_{\text{max,s}}$      | <748 m           |
| $H_{\text{min,d}}$      | >-10 m           |
| $N_{\text{max,t}}$      | <45%             |

3.2. Hydraulic Disturbance Test

Hydraulic disturbance test is to verify the influence of one unit’s load rejection on the other normal operating unit. This part mainly focuses on the output variation and the WG opening of the disturbed unit. This station is integrated into the East China Power Grid, whose capacity is big enough, so there is little possibility to adopt isolated frequency regulation. Besides, hydraulic disturbance has little effect on the output of the normal operating unit under isolated frequency regulation, so this operation mode was not considered. The test conditions of hydraulic disturbance are as follows.

Condition of test 3: the upstream water level is 728.63 m and the downstream water level is 287.17 m. The load of unit 1 is 297.3 MW and the load of unit 2 is 226.1 MW. Unit 1 rejects full load while unit 2 operates normally.

Condition of test 4: the upstream water level is 727.95 m and the downstream water level is 290.78 m. The load of unit 1 is 299.4 MW and the load of unit 2 is 300.50 MW. Unit 1 rejects full load while unit 2 operates normally.

The main evaluation index of hydraulic disturbance is output variation. The output of a generator is the product of current and voltage. The voltage stays stable due to the characteristics of excitation regulation. Therefore, the output variation is mainly shown as the change of current over time. The generator can operate under overcurrent condition in a short time. According to the operation requirements of the power grid, the control criteria are shown in Table 2.

| Multiplier of overcurrent (Actual current/Rated current) | Allowable duration (s) |
|----------------------------------------------------------|------------------------|
| 1.25                                                      | 288.15                 |
| 1.30                                                      | 231.14                 |
| 1.40                                                      | 162.87                 |
| 1.50                                                      | 124.01                 |
3.3. Comparative Principle
The boundary condition in the simulation was exactly the same as that in the field test, ensuring the comparison correct. The turbine flow, pipe pressure and gate opening in the initial state were calculated by upstream water level, downstream water level and unit output in the field tests. With the same closing law, the load rejection transient process was calculated by simulation software. (the software used in the calculation is HYSIM, which was developed for the simulation of hydraulic-mechanical transient process by Huadong Engineering Corporation Limited)

The calculation error of fluctuating pressure, speed and output were obtained by comparing the numerical result with the test value. It can be found from the test that the fluctuating pressure is larger when the WG is blocked and relatively small when the WG is closing, as shown in Figures 3-4. So the load rejection process is divided into two periods in order to improve the accuracy of fluctuating pressure correction. The former is blocked period and the latter is closing period.

For the $H_{\text{max,s}}$ and the $H_{\text{min,d}}$, relative calculation error=$(\text{numerical result-test value})/\text{net pressure before load rejection}$.

For the $n_{\text{max,t}}$ and the $N_{\text{max,u}}$, calculation error=$\text{numerical result-test result}$.

![Figure 3. Pressure of spiral case versus time.](image)

![Figure 4. Pressure of draft tube versus time.](image)

4. Comparison Between Test and Calculation

4.1. Comparison under Double Units Load Rejection
In the same boundary, the filed test values and numerical calculation results under condition of double units load rejection were shown in Table 3-9 and Figures. 5-8.

| Condition | Unit | Blocked period | Closing period |
|-----------|------|----------------|----------------|
|           |      | Test value(m)  | Numerical result(m) | Test value(m)  | Numerical result(m) |
| Test 1    | 1#   | 642.88         | 600.50            | 578.01         | 616.46          |
|           | 2#   | 649.11         | 611.84            | 579.01         | 621.68          |
|           | 1#   | 680.54         | 619.80            | 608.45         | 650.55          |
| Test 2    | 2#   | 677.79         | 618.90            | 614.44         | 653.77          |

| Condition | Unit | Blocked period | Closing period |
|-----------|------|----------------|----------------|
|           |      | Test value(m)  | Numerical result(m) | Test value(m)  | Numerical result(m) |
| Test 1    | 1#   | 40.78          | 70.95            | 56.79          | 65.46          |
|           | 2#   | 42.68          | 66.24            | 58.17          | 64.90          |
|           | 1#   | 37.54          | 63.70            | 46.13          | 51.45          |
| Test 2    | 2#   | 38.98          | 64.92            | 46.93          | 50.22          |
### Table 5. Maximum rise rate of turbine speed.

| Condition | Unit | Test value | Numerical result |
|-----------|------|------------|------------------|
| Test 1    | 1#   | 28.10      | 29.19            |
|           | 2#   | 28.50      | 29.20            |
| Test 2    | 1#   | 38.30      | 38.61            |
|           | 2#   | 39.10      | 38.75            |

![Figure 6. WG opening versus time.](image)

![Figure 7. Pressure in spiral case versus time.](image)

![Figure 8. Pressure in draft tube versus time.](image)

![Figure 9. Turbine speed versus time.](image)

It is shown in Table 3 and Figure 3-9 that, without considering fluctuating pressure, the numerical results are in good agreement with that of the test, verifying the reliability of the simulation software HYSIM. The fluctuating pressure has a lot of influence on the maximum pressure and can’t be ignored in the transient process.

In order to ensure the safety of the station, it is necessary to recheck the pressure and speed under extreme conditions that may occur in the future. The calculation results should be corrected according to the principle in Chapter 2. The calculation errors of pressure and speed were shown in Table 10.

### Table 10. Errors of characteristic parameter.

| Characteristic parameter | Blocked period | Closing period |
|--------------------------|----------------|----------------|
| $H_{\text{max,s}}$ (%)   | -13.52         | 4.65           |
| $H_{\text{min, d}}$ (%)  | 7.38           | 2.24           |
| $H_{\text{max, t}}$ (%)  | -1.18          |                |

#### 4.2. Comparison under Hydraulic Disturbance

In the same boundary, filed test values and numerical calculation results under hydraulic disturbance condition were shown in Table 11 and Figures 9-10.
Table 11. Test values and calculation results under hydraulic disturbance rejection.

| Condition | Test value (MW) | Numerical result (MW) | Error value (MW) |
|-----------|-----------------|-----------------------|-----------------|
| Test 3    | 288.13          | 304.23                | 15.60           |
| Test 4    | 363.30          | 389.82                | 26.52           |

Figure 9. WG opening of disturbed unit versus time under condition test 4.

Figure 10. Output of disturbed unit versus time under condition test 4.

It is shown in Table 7 and Figure 9-10 that the disturbed turbine is in power regulation. The WG variation is to keep the output constant. The numerical result is close to and slightly larger than that of the test, for there is a certain delay of the WG opening in the adjustment. However, as time changes, the numerical results are in good agreement with that of the test. The numerical simulation results can be used to predict extreme conditions.

5. Inversion under Extreme Conditions

Extreme conditions such as reservoir flood may occur in the future, threatening the safe operation of the station. It is necessary to recheck the pressure, speed and output under load rejection and hydraulic disturbance conditions. Field test is unsafe and unrealistic under such condition, so numerical simulation by the software is a practical method. The results of the simulation calculation should be corrected and then compared with the design values. The specific error values were calculated in Chapter 3.

5.1. Inversion under Double Units Load Rejection

The maximum $H_{\text{max},s}$ and the minimum $H_{\text{min},d}$ occur in the condition that the upstream water level reaches maximum and two units reject load successively. It is because the WG closing of the former unit causes flow increase of the latter, which enters deeply into “anti-pump area”. So the water hammer pressure is greater during the transient process.

The maximum $n_{\text{max},l}$ occurs in the condition that two units both reject full load at rated water head and rated flow. The WG of one unit closes normally, while that of the other is blocked. It is because in the early 10s, the WG of both turbines remain still and the speed is the same. In the later 25s, the WG of one unit is closed normally, which will lead to flow increase of the other unit and higher rise of the turbine speed.

Numerical calculation was carried out under extreme conditions. The results were corrected in aspect of fluctuating pressure based on previous analysis. The results were shown in Table 12.

Table 12. Calculation results under extreme load rejection conditions.

| Relative gate opening (%) | Time (s) | Test value | Numerical value |
|--------------------------|---------|------------|-----------------|
|                           | 50      | 100        | 90              |
|                           | 40      | 85         | 75              |
|                           | 30      | 80         | 70              |
|                           | 20      | 75         | 65              |
|                           | 10      | 70         | 60              |

| Unit output (MW) | Time (s) | Test value | Numerical value |
|-----------------|---------|------------|-----------------|
|                 | 50      | 400        | 350             |
|                 | 40      | 350        | 300             |
|                 | 30      | 300        | 250             |
|                 | 20      | 250        | 200             |
|                 | 10      | 200        | 150             |

6
| Characteristic parameter | Numerical result | Corrected result | Design value |
|--------------------------|-----------------|-----------------|--------------|
|                           | Blocked period  | Closing period  | Blocked period | Closing period |             |
| $H_{\text{max},s}$ (m)   | 643.67          | 679.9           | 708.92        | 658.11         | 748         |
| $H_{\text{min},d}$ (m)   | 25.11           | 4.22            | -7.23         | -6.28          | -10         |
| $n_{\text{max},t}$ (%)   | 41.09           | 42.27           | 45            |                |             |

It is shown in Table 6 that after correction, the $H_{\text{max},s}$ is 708.92 m and the $H_{\text{min},d}$ is -7.23 m. The revised value meets the requirements for guaranteed regulation calculation and have some degrees of safety margin. So the water conveyance system and the unit are all safe under extreme condition.

5.2. Inversion under Hydraulic Disturbance

According to the operation, the selected extreme condition of hydraulic disturbance is: the upstream water level is 743.79 m and the downstream water level is 266.00 m; two units running at rated output; unit 1 rejects full load while unit 2 operates normally.

Numerical calculation was carried out under extreme conditions. The results were corrected in aspect of output based on previous analysis. The results are shown in Table 13 and Figure 12.

Table 13. Calculation results under extreme load rejection conditions.

| Frequency regulation in ILPG | Power regulation in ILPG |
|-----------------------------|--------------------------|
| $N_{\text{max},u}$ (MW)     | $N_{\text{max},u}$ / rated output | $N_{\text{max},u}$ (MW) | $N_{\text{max},u}$ / rated output |
| 404.80                      | 1.349                     | 404.03                    | 1.347                     |

There is no hydraulic disturbance test under frequency regulation in ILPG. Besides, the WG opening keeps unchanged in this mode so the calculation error is smaller. Therefore, the calculation results were corrected according to the error value in power regulation in ILPG.

It is shown in Table 7 and Fig. 12 that, the $N_{\text{max},u}$ is 404.80 MW under extreme condition. The value decreases to 378.28 MW after correction, meeting the design requirement of overcurrent intensity. The duration is less than 30s, meeting the operating and scheduling requirements of power grid. Under operation mode of frequency regulation in ILPG, the effect of hydraulic disturbance is great on the output of the normal operating unit and the overcurrent is the highest. Therefore, it is the control condition of the overcurrent intensity design of the unit. Sufficient attention should be paid to this mode in the calculation of hydraulic disturbance.

6. Conclusions

(1) The “$S$” area is steep and the effect of “flow interception” is significant in this power station. The innovative closing law can reduce the $H_{\text{max},s}$ and $H_{\text{min},d}$ to a certain extent.

(2) According to the field test, fluctuating pressure is greatly influential to the $H_{\text{max},s}$ and $H_{\text{min},d}$ in the load rejection transient process. In the inversion calculation, the accuracy can be improved by dividing the process into blocking period and closing period.

(3) The numerical calculation results agree well with that of the field test values under both load rejection and hydraulic disturbance conditions, verifying the reliability of the software HYSIM. It is not suitable to do field test under extreme condition, so the inversion calculation based on simulation software is an important method to check the safety of the water conveyance system and the unit. The inversion results in this power station meet its design requirements.

(4) Although the innovative closing law can reduce the hammer pressure in the transient process, it also causes a lot of problems: long load rejection process, intense unit vibration, large amplitude of the fluctuating pressure, large noise in the field and so on, which increase the risk of unit failure. Therefore, it is only a remedy and also the last resort for the improvement of the pressure extremum during the load rejection. In the long term, it is suggested that the stability and hydraulic performance of the unit should be emphatically studied in hydraulic development stage, in order to improving the unit performance.
The study provides references for the design and operation of this station. The inversion process under extreme condition provides experience in high precision simulation for other pump storage power station.

**Notation**
The following symbols are used in this paper:

- \( WG \) = wicket gate
- \( ILPG \) = ideal large power grid
- \( H_{\text{max,s}} \) = maximum pressure in the spiral case
- \( H_{\text{min,d}} \) = minimum pressure in the draft tube
- \( n_{\text{max,t}} \) = maximum rotating speed of the turbine
- \( N_{\text{max,u}} \) = maximum output of the normal operating unit

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