Double Units Load Shedding Test and Simulation Analysis of Hydropower Station with Tailrace Surge Tank

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ABSTRACT

Double units load shedding transient process of tailrace surge chamber shared is analyzed by field test and numerical simulation. The transient process simulation model is examined by field test. Based on the measured data, pulsation pressure of load rejection transient process at draft tube inlet was extracted by using the method of signal analysis, and it is applied to transient calculation. The impedance factor of the surge chamber, the rotary inertia of hydroelectric generating set, the model and parameters of the governor are identified and obtained respectively by using the measured data. The more accurate simulation model of the transient process is established, which makes the simulation results highly consistent with the test results. The model can be used to predict the double load rejection transition process under extreme conditions so as to ensure the safe operation of hydropower plants.

Keywords: transient process; load shedding; tailrace surge tank; numerical simulation

INTRODUCTION

Due to the restrict of topography and geological conditions, the head or middle way development mode is used in many underground hydropower stations, which have a long tailrace system and set up tailrace surge tank. For the double units sharing one tailrace surge tank and one main transformer, the probability of load shedding of double units at the same time is extremely high. In order to ensure the safety of units, it is necessary to make a detailed analysis of the double units load shedding transient process.

The method of field test combined with simulation is adopted in the research of load rejection transient process at present. Load shedding test is an important method to demonstrate the performance of load shedding transition process[1]. However, due to the limitation of test conditions, the performance of load shedding transition process under extreme conditions cannot be obtained and needs to be further analyzed through simulation calculation. The calculation results depend on the mathematical model and the values of various parameters[2]. In order to improve the accuracy of simulation calculation, it is necessary to verify the simulation model and identify important parameters based on field test.
The test technology of double load shedding process has been mature. A large number of field measurement data has been obtained through field tests. Some field test results have also been compared with simulation results[3]. However, there is no specific and systematic analysis of the reasons for the differences between simulation and test results, and the simulation model and parameters are not identified according to the test results. The design parameters were taken into the simulation model, which created the differences between the simulation and the test.

In this paper, double units load shedding test of hydropower station with tailrace surge tank is carried out. The results of test are analyzed. The simulation model is corrected according to field measurements, and the important parameters are measured and identified, which can make simulation results reflect the actual situation more accurately, and the performance of the load shedding process under extreme conditions is analyzed using the accurate simulation model.

TEST RESULTS OF LOAD SHEDDING

For a hydropower station, the layout of one tunnel with one turbine arrangement is adopted into the diversion system, and the layout of one tunnel with two turbines which share one tailrace surge tank is adopted into the tailrace system. The expansion unit connection is used in the main electrical connection. Hydro turbine type is A855, rated head is 128m, rated flow is 218.21m$^3$/s, rated speed is 166.67r/min, rated output of hydro turbine is 256.5MW, GD$^2$ which designed is 29500t.m$^2$.

Disconnecting the breaker of the high-voltage side of the main transformer is used into the double units’ load shedding test. Before the test, No. 1 and No. 2 unit were on-load, and then 50%, 75% and 100% rated load shedding test were carried out in the order. After each load rejection test, there is comparative analysis between test results and standards, and the rotating parts of two units are comprehensively checked. During the test, the units’ frequency, guide vane opening, circuit breaker position, spiral casing inlet pressure, draft tube inlet pressure and water level of surge tank were recorded by test instrument.

Test results of two units load shedding 100% of the rated load are shown in Figure 1 to Figure 3. In the test, due to the high installation position of the surge tank water level sensor and the large fluctuation of the water level, the minimum surge was lower than the installation elevation of the sensor, so some test results of the surge tank water level measured in Figure 3 has lost in the first trough of the wave.
SIMULATION MODEL AND PARAMETERS ACQUISITION

The simulation theory of large fluctuation transient process of hydropower generating system with surge chamber has been mature. The continuity equation and the motion equation of pressurized water conveyance system are solved by the method of characteristic line method. The boundary of reservoir, surge chamber and hydro turbine are combined to calculate the entire system transient process[2].

However, for the calculation of the draft tube pressure in the large fluctuation calculation, only the water hammer pressure can be calculated and the pulsating pressure caused by the pressure pulsation of the hydro turbine can’t be obtained. For the high head hydropower station, the value of pressure pulsation is generally larger, which affects the change process of draft tube inlet pressure. Therefore, in order to accurately analyze the vacuum in the draft tube after load rejection, it is necessary to calculate the pressure pulsation accurately, and obtain the pressure variation process of the draft tube inlet.

In the calculation of large fluctuation transient process, the important parameters are usually obtained from design, which also affects the accuracy of the transient process calculation, such as impedance coefficient of the surge chamber[4], unit( including generator, turbine and rotating water) moment of inertia. These two parameters of ten cannot be accurately obtained through the design, only can be calculated and identified by the field test.

At present, the guide vane opening model is often used as turbine governor model in the calculation of large fluctuation transient process [5],the variation of guide vane opening is given to avoid solving the governor equations, it can simplify the simulation model, but the regulation process of the unit speed can’t be accurately obtain and the dynamic quality of the hydro turbine governor can’t be analyzed and evaluated.

Extraction of Draft Tube Inlet Pressure Pulsation

For the hydroelectric units with tailrace surge tank, the draft tube inlet pressure after load rejection is mainly composed of water hammer pressure, surge water level fluctuation and pressure pulsation. The frequency of water hammer pressure and the surge tank water level is very low, while the pressure pulsation frequency is much higher. Pressure pulsation
value at the draft tube inlet can’t be accurately calculated by one-dimensional transient process calculation. Although three-dimensional CFD technology can get pressure pulsation, it is necessary to obtain a detailed turbine blade model which usually would not be provided by the hydro turbine manufacturer, and the research shows that there are some differences between the pressure fluctuation obtained by CFD calculation and the field test[6].

In order to accurately obtain the pressure change process of draft tube in let in the load rejection, the test results of the draft tube inlet pressure can be analyzed, and the pressure pulsation can be extracted as a correction term and applied to the inlet pressure of the draft tube calculated by the one-dimensional transition process.

Figure 4 shows spectrum analysis results of the pressure pulsation measured. From the result, the main frequency components include 0.011Hz, 10Hz, 40Hz and 60Hz. According to the basic theory of hydraulic turbine, it can be concluded that the frequency components above 10Hz are the pressure pulsation components of hydraulic turbine.

The measured pressure of draft tube inlet is filtered and analyzed, and the high pass and low pass filtering are carried out with 2Hz as the boundary. The results are shown in Figure 5. After the low-pass filtered, the signal shows more regular periodic fluctuations, which is basically consistent with the fluctuation period of the tailrace surge tank water level (as shown in Figure 3). After the high-pass filtered, signal is mainly the pressure fluctuation of the draft tube, which is as the correction value of the draft tube inlet pressure of transient process calculation.

**Extraction of The Impedance Coefficient of Surge Chamber**

For the impedance surge chamber, the calculation formula of surge tank water level is shown in equation (1). $H$ is the surge chamber pressure of the bottom. $Z$ is the surge
chamber water level. \( Q_T \) is the flow into the surge chamber. \( \alpha_f = \frac{1}{2g} \left( \frac{1}{\varphi S} \right)^2 \) is the impedance coefficient of surge chamber, where \( S \) is the area of impedance orifice, \( \varphi \) is flow coefficient of impedance pore. The area of the surge chamber and the impedance orifice can be obtained according to the design accurately. The value of the impedance coefficient is generally based on the empirical value, which directly affects the calculation result of the surge in surge chamber.

\[
H = Z - \alpha_f Q_T |Q_T| (1)
\]

The comparison between the calculated and the test results of the surge at different \( \varphi \) values of the surge chamber is shown in Figure 6, by this result, a set of impedance coefficients with good agreement with the test results can be obtained.

![Figure 6. Comparison between calculated results of surge with different impedance coefficients and test results.](image)

**Governor Model and Parameter Identification**

Load shedding test is also an important means to test the control performance of hydro turbine governor. For large hydropower units, both of the GCB and TCB position signal are connected to the hydro turbine governor, so governor will switch grid mode to off grid mode in double units' load test rejection, and the governor undergoes two stages of rapid closing and frequency control. In the rapid closing stage, the guide vane is closed according to the law which is set in the governor, and in the simulation, only the guide vane closing law is needed. In the frequency control stage, the governor will be adjusted according to the frequency deviation, so a more detailed governor control model is needed in the simulation.

The governor model mainly includes the regulator model and the guide vane servo system model. The regulator is mainly controlled by PID. After a large number of field tests, the PID control in large hydropower units is basically the same as the theoretical model, and the set parameters can also be directly used in the simulation. According to the model and identification method recommended by literature [7], the integral time constant of guide vane closing action is obtained according to the perturbation test of the guide vane opening. \( T_c = 11.14s \), \( V_{EL\text{close}} = -1 \). The integral time constant of guide vane opening action is \( T_o = 11.14s \), \( V_{EL\text{open}} = 0.61 \), and PID parameters of guide vane opening hydraulic system: \( K_{PE} = 70 \), \( K_{IE} = 0 \), \( K_{DE} = 0 \).

**Measurement of Rotary Inertia of Hydroelectric Generating set**

The rotary inertia of hydroelectric generating set directly affects the units’ speed change process in load shedding. In transient process calculation, the rotary inertia of the hydroelectric generating set should include the generator, hydro turbine and rotating body of water. Only the rotary inertia of generator can be obtained by design data, and the more accurate rotary inertia needs to be obtained by measurement.
The rotary inertia of hydroelectric generating set can be measured by more than 50% of rated load shedding test \cite{7}. The first order equation of the generator is shown in formula (2), where: \[ T_a = \frac{GD^2 n_r^2}{3580 P_r} \] \( GD^2 \) is the flywheel torque of the unit, \( n_r \) is the rated speed and \( P_r \) is the rated output. \( m_g \) is the generator load torque deviation relative value. \( m_t \) is the hydro turbine torque deviation relative value.

\[ T_a \frac{dx}{dt} = m_t - m_g \]  \( \text{(2)} \)

Speed change process of load shedding unit is shown in Figure 7. There is a fixed time when the governor acting, in the fixed time the unit speed rises and the guide vane does not close. So the inertia time constant \( T_a \) and \( GD^2 \) can be obtained according to the following formula.

\[ T_a = \frac{1/\Delta F}{50/\Delta t} = \frac{1/0.931Hz}{50/0.198s} = 10.652 \]  \( \text{(3)} \)

![Figure 7. Test results of unit speed and guide vane opening in the load shedding test.](image)

**Comparative Analysis of Simulation and Measured Results**

The measured data can be used to correct the mathematical model which can be used to simulate the transient process of 100% rated load rejection. The simulation results are compared with the measured results as shown in Figure 8-9.

It can be obtained through comparison: 1) The simulation of draft tube entrance pressure is in good agreement with the measured data, which shows that the mathematical model can not only simulate the water hammer pressure and mean pressure caused by surge, but also accurately simulate the pulsating pressure of draft tube entrance; 2) The simulation of the extreme and change process of spiral casing entrance pressure is in good agreement with the measured data, and after guide vane closed vibration phenomenon exist because of calculation instability at the zero guide vane opening; 3) The simulation result of water level in the surge tank is consistent with the measured result; 4) The simulation results of guide vane opening and the unit speed are consistent with the measured result, that indicates the governor model and the rotary inertia which used in simulation are accurate.
SIMULATION RESULTS UNDER EXTREME CONDITIONS

The performance of the load rejection transient process of hydro turbine under different heads is different. The extreme conditions would be calculated in the large-fluctuation transient process calculation in the design of hydropower station. However, the calculation model is rather rough and generally used for the feasibility study of a project. It is difficult to carry out load shedding test in extreme conditions due to the limitation of hydro turbine operating conditions. So the more accurate mathematical models can be used to analyze the load shedding transient process performance in these conditions comprehensively and accurately to ensure safe operation of hydropower units.
The calculation model which is corrected by the test can be used to calculate the transient process of double units load shedding of 100% rated load under rated head and maximum head. The calculation results are shown in Table I. It can be seen that draft tube vacuum under the rated head is slightly larger than that under the maximum head, and the spiral casing pressure, the water level of the surge tank and the speed rise of the unit under the maximum head are all larger than that under the rated head.

Table I. Simulation results under extreme conditions.

<table>
<thead>
<tr>
<th>conditions</th>
<th>maximum spiral casing entrance pressure (m)</th>
<th>minimum draft tube entrance pressure(m)</th>
<th>Maximum unit speed rise (%)</th>
<th>Maximum water level of surge tank (m)</th>
<th>Minimum water level of surge tank (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>rated head</td>
<td>155.92</td>
<td>-3.8</td>
<td>44.00</td>
<td>326.1</td>
<td>311.73</td>
</tr>
<tr>
<td>maximum head</td>
<td>178.43</td>
<td>-3.73</td>
<td>45.19</td>
<td>325.71</td>
<td>312.87</td>
</tr>
</tbody>
</table>

CONCLUSIONS

In this paper, the test and simulation analysis of double units load shedding transient process of hydropower station with tailrace surge tank are carried out. The simulation model of the transient process is studied by field test data. The pulsating pressure at the draft tube entrance of the load rejection transient process is obtained by signal analysis and extraction of test data and applied to the calculation. The impedance coefficient of the surge tank was identified by the test data. Based on field test, the governor model and parameters were identified, and a more accurate governor model was obtained. The rotary inertia of hydroelectric generating set was calculated based on the unit’s frequency change process of load shedding test. Therefore, a more accurate simulation model of double units load shedding of hydropower station with tailrace surge tank is established. The calculated results are in good agreement with the measured results by comparison. The precise calculation model issued to predict the load shedding process under the rated head and the maximum head conditions to ensure the safety operation of hydropower plant.

REFERENCES