Test analysis and solution of insufficient output of hydraulic turbine

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Abstract. The article analyzes the factors that cause the insufficient output of hydraulic turbine, tests and analyzes the output, head and flow of the turbine, finds out the cause of the insufficient output of the turbine and proposes a solution.

1. Overview
The installed capacity of a hydropower station is 100MW, which is a single power generation project and has no comprehensive utilization requirements. The power plant cited a flow rate of 562.6m³/s, a designed water head of 20m, a storage capacity of 22.1 million m³, and a regulated storage capacity of 2.6 million m³. The maximum height of the dam is 42.8m, the height of the crest of the dam is 630.8m, the normal storage level of the reservoir is 623.0m, the dead water level is 622.0m, and the design flood level is 625.33m. It has daily adjustment capacity and has an average annual power generation of 46.31 million kW.h. The hour is 4603 hours.

The power station was built in June 2014 and connected to the grid for power generation. After five years of operation, it was found that at the upstream storage level of 623m, the output of the single unit met the design requirements (50MW), and the design value could not be reached when the two units were simultaneously loaded.

In order to excavate the cause of the power plant's insufficient output and seek improvement measures, the output test of the hydro-generator set was conducted in 2019. Through the analysis of the measured data, the cause of the insufficient output of the hydro turbine was discussed.

2. The main factors affecting the output of the hydroelectric generating set
The output of the hydro-generator set can be calculated by the following formula:\(^1\):

\[ N = \gamma QH\eta \]  

In the formula: N is the output of the hydroelectric generating set(kW);
\(\gamma\) is the severity of water, 9810N/m³;
Q is turbine flow(m³/s);
H is net head of turbine(m);
\(\eta\): unit efficiency, including turbine efficiency and generator efficiency.

From equation (1), the factors affecting the output of the turbine include the flow Q, the net head H and the efficiency \(\eta\) of the turbine and these three factors are closely related to design, manufacturing, and operation. By testing the above three parameters, you can accurately find out the cause of the insufficient output of the turbine, and then propose solutions.
2.1. Main technical parameters of the unit

| Water turbine | Generator |
|---------------|-----------|
| Model number  | ZZ-HL-620 | Model number | SF50-56/9900 |
| Rated head    | 20.7m     | Rated power  | 51550kW       |
| Rated speed   | 107.1rpm  | Rated voltage| 10500V        |
| Flying speed  | 310rpm    | Rated current| 3234.5A       |
| Rated flow    | 270.8 m³/s| Rated frequency| 50Hz          |

2.2. Parameter measurement

2.2.1. Power measurement

A portable power recording analyzer is used to collect and measure the voltage and current of the PT and CT on the machine side to calculate the active power and reactive power of the unit.

2.2.2. Net head measurement

The hydraulic head of the turbine is calculated as follows: \[
H = \frac{\Delta P \times 10^6}{\gamma} + \frac{\left( V_1^2 - V_2^2 \right)}{2g}
\]  

In the formula: \( \Delta P \) is the pressure difference between the inlet of the volute and the outlet of the draft tube (MPa), measured with a pressure sensor with an accuracy of 0.2%;  
\( \gamma \) is the severity of water, 9810N/m³;  
\( V_1 \) is the average velocity of the water flow at the inlet of the volute (m/s);  
\( V_2 \) is the average velocity of the water flow at the outlet of the draft tube (m/s);  
\( g \) is the acceleration of gravity(m/s²)  

2.2.3. Flow measurement

The flow rate is measured by the volute pressure difference method, and the calculation formula is as follows:  
\[
Q = K \sqrt{\Delta h}
\]  

In the formula:  
\( K \) is the pressure difference coefficient and constant of the volute, measured by model test;  
\( \Delta h \) is the pressure difference between the inner and outer points of the same cross-section of the volute, measured by a pressure difference sensor with an accuracy of 0.2%.

2.3. Test results

The test is conducted in the following three steps:

(1) The 2F unit is in a stopped state, and the 1F unit has 30% rated load, 50% rated load, 75% rated load and 100% rated load respectively;
(2) The 1F unit is in a stopped state, and the 2F unit has 30% rated load, 50% rated load, 75% rated load and 100% rated load respectively;
(3) The two units are simultaneously loaded with 30% rated load, 50% rated load, 75% rated load and 100% rated load.

Test sensor installation instructions:

(1) The relevant original parameters of Unit 1: volute pressure sensor elevation: ▼600.565m, draft tube pressure sensor elevation: ▼591.21m, sensor elevation difference: 9.355m;
(2) The relevant original parameters of Unit 2: volute pressure sensor elevation: ▼600.5m, tail water pressure sensor elevation: ▼590.966m, sensor elevation difference: 9.535m.

The results of each measurement are shown in Table 1 to Table 3.
Table 1: 1F unit single machine output test results.

| Active power (MW) | Upstream water level (m) | Downstream water level (m) | Guide vane opening (%) | Flow (m³/s) | Inlet pressure of volute (MPa) | Outlet pressure of draft tube (MPa) | Gross head (m) | Net head (m) | Head loss (m) |
|-------------------|--------------------------|----------------------------|------------------------|-------------|-------------------------------|------------------------------------|----------------|--------------|---------------|
| 17.977            | 622.7                    | 600.95                     | 50.93                  | 100.107     | 0.21                          | 0.094                              | 21.75          | 21.187       | 0.563         |
| 26.314            | 622.7                    | 601.22                     | 64.28                  | 146.102     | 0.208                         | 0.096                              | 21.48          | 20.779       | 0.701         |
| 39.167            | 622.7                    | 601.48                     | 80.53                  | 220.502     | 0.203                         | 0.098                              | 21.22          | 20.065       | 1.155         |
| 50.439            | 622.66                   | 601.83                     | 94.32                  | 312.386     | 0.191                         | 0.101                              | 20.83          | 18.535       | 2.295         |

Table 2: 2F unit single machine output test results.

| Active power (MW) | Upstream water level (m) | Downstream water level (m) | Guide vane opening (%) | Flow (m³/s) | Inlet pressure of volute (MPa) | Outlet pressure of draft tube (MPa) | Gross head (m) | Net head (m) | Head loss (m) |
|-------------------|--------------------------|----------------------------|------------------------|-------------|-------------------------------|------------------------------------|----------------|--------------|---------------|
| 17.931            | 622.8                    | 601.03                     | 47.8                   | 103.583     | 0.212                         | 0.103                              | 21.77          | 20.653       | 1.117         |
| 26.056            | 622.8                    | 601.18                     | 60.44                  | 147.802     | 0.210                         | 0.104                              | 21.62          | 20.347       | 1.273         |
| 38.48             | 622.8                    | 601.43                     | 75.78                  | 220.257     | 0.207                         | 0.107                              | 21.37          | 19.735       | 1.635         |
| 51.356            | 622.78                   | 601.73                     | 88.32                  | 316.718     | 0.198                         | 0.108                              | 21.05          | 18.715       | 2.335         |

Table 3: Test results of double-machine simultaneous load output test.

| unit   | Active power (MW) | Upstream water level (m) | Downstream water level (m) | Guide vane opening (%) | Flow (m³/s) | Inlet pressure of volute (MPa) | Outlet pressure of draft tube (MPa) | Gross head (m) | Net head (m) | Head loss (m) |
|--------|-------------------|--------------------------|----------------------------|------------------------|-------------|-------------------------------|------------------------------------|----------------|--------------|---------------|
| 1F     | 17.749            | 622.78                   | 601.38                     | 51.33                  | 100.920     | 0.212                         | 0.098                              | 21.40          | 20.983       | 0.417         |
| 2F     | 17.669            | 622.78                   | 601.38                     | 47.47                  | 103.605     | 0.212                         | 0.106                              | 20.347         | 1.053        |
| 1F     | 26.037            | 622.78                   | 601.83                     | 65.01                  | 147.461     | 0.208                         | 0.101                              | 20.269         | 0.681        |
| 2F     | 25.62             | 622.78                   | 601.83                     | 61.21                  | 149.065     | 0.21                          | 0.109                              | 19.837         | 1.113        |
| 1F     | 38.313            | 622.65                   | 602.43                     | 82.02                  | 227.731     | 0.201                         | 0.106                              | 19.045         | 1.175        |
| 2F     | 37.878            | 622.65                   | 602.43                     | 77.6                   | 229.115     | 0.204                         | 0.114                              | 18.715         | 1.505        |
| 1F     | 46.111            | 622.5                    | 603.13                     | 95.42                  | 314.521     | 0.19                          | 0.114                              | 17.107         | 2.263        |
| 2F     | 47.758            | 622.5                    | 603.13                     | 91.56                  | 320.601     | 0.196                         | 0.12                                | 17.287         | 2.083        |

3. Test data analysis
From the analysis of experimental data, the main reason for the insufficient output of the unit is the low net head of the turbine.
There are two reasons for the low net head: first, when the two machines are running, due to the large total flow, the downstream water is not well drained, causing the downstream water level to rise by nearly 2 meters; Secondly, due to the increase of the downstream water level, the gross head of the turbine is reduced, and the flow of the turbine under the same output increases, which increases the head loss and further reduces the working head of the turbine.

It can be seen from test data and the running characteristic curve of ZZ-HL-620 in Figure 1, When the maximum output of the two units is due to the rise of the downstream water level and hydraulic loss, the net head is 17.107m~17.287m, which is about 3m lower than the designed head. The operating head of the power station deviates seriously from the design head, which prevents the hydrogenerator set from reaching the designed output.

4. Conclusion
Through the analysis of the test data, the reason for the insufficient output of the turbine is that the downstream water level is raised and the head loss is too large, and the turbine cannot reach the design head. It can be solved by raising the upstream water level or lowering the downstream water level, thereby increasing the operating head. Because the reservoir area is restricted by the water storage level, it is not possible to raise the upstream water level for operation. Therefore, the solution to the insufficient output of the turbine is to treat the downstream river channel to reduce the downstream water level and increase the operating head.

In the winter of 2019, the downstream river channel was treated to reduce the downstream water level, and the output of the hydro-generator set reached the design value.

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