Analysis of Small Fluctuation Stability of Upstream and Downstream Double Surge chamber Diversion Power Generation System

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Abstract. Installation of upstream and downstream surge chamber is a significant and feasible measure for peak pressure control in the hydropower system with long water diversion and drainage tunnel. This paper presents a study on the fluctuation stability with such a measure. For this system, a complete mathematical model including diversion pipeline, upstream surge tank, hydraulic turbine and downstream surge tank was developed, calculating the hydraulic transition characteristics and analyzing the fluctuation stability with different surge tank cross areas. The calculation shows that, the hydropower system with upstream and downstream surge chamber, can also be stable even if the surge tank cross area is smaller than the calculated value. In practice, in the condition of meeting the stability requirement, multiple schemes should be calculated in order to find out the minimum areas to reduce project investment.

1. Introduction

Fluctuation stability is that, after suffering a slight disturbance, the hydropower system recovers to its original status or maintains in a new equilibrium state under the action of the governor or other control equipment. The stability here only refers to the water regulating process and it does not contain operating index of generating units such as vibration. Little fluctuation is frequent when hydropower station is running, so it is particularly important to analyze the stability of little fluctuations.

Due to terrain factors, some hydropower stations need to be designed as underground powerhouse, causing the water diversion and drainage tunnel pressurized and longer. In this condition, installation of upstream and downstream surge chamber is usually used to balance the water pressure. At present, there are fewer hydropower stations that have been built with upstream and downstream surge chamber, and the studies on the little fluctuation are less either. Reference [1] derived the calculation formulas of upstream and downstream surge chamber cross areas, and analyzed how the governor parameters affected the little fluctuation stability in the condition of the unit moment of inertia, the turbine torque and the surge tank area were certain. Reference [2] studied water level fluctuation stability condition, and a case calculation was made to verify its availability. Reference [3] studied the factors that can influence the fluctuation in diversion system with double surge chamber upstream, and it showed that if the distance between the two surge chamber was longer, the total cross areas were larger, and the surge tank near the unit influenced the fluctuation more than the other one.
The size of the surge chamber cross areas directly affects the hydropower project investment. In the condition of meeting the stability requirement, using the smaller surge tank will largely reduce the project investment cost. This paper established a mathematical model for hydropower system with upstream and downstream surge chamber based on the characteristics method\cite{4}, calculated the little fluctuation hydraulic transition process in the condition of different surge chamber areas, and studied how the surge chamber areas affected the little fluctuation stability. The calculation shows that, the hydropower system with upstream and downstream surge chamber, can also be stable even if the surge tank cross area is smaller than the calculated value. In practice, in the condition of meeting the stability requirement, multiple schemes should be calculated in order to find out the minimum areas to reduce project investment.

2. Mathematical model

2.1. Basic assumptions

In analysis of little fluctuation stability, some assumptions are made as follows\cite{5}:

- The turbine speed, water head and guide vane opening are certain.
- To ignore the voltage fluctuation.
- The turbine-generator unit is not connected to the power grid.
- To ignore adjustment coefficient of load.
- Governor permanent difference coefficient is 0.

2.2. Mathematical model

Hydropower system with long water diversion and drainage tunnel consists of reservoir, water diversion tunnel, surge tank, penstock, spiral casing, turbine, draft tube and drainage tunnel. In the little fluctuation working condition, the elasticity of water and pipe wall can be ignored, and rigidity water hammer theory can be used to analyze the hydraulic transition. Fig.1 shows the hydropower system with upstream and downstream surge chamber.

\begin{equation}
\frac{\partial V}{\partial t} + V \frac{\partial V}{\partial x} + g \frac{\partial H}{\partial x} + g \frac{fV|V|}{2D} = 0
\end{equation}

\begin{equation}
\frac{\partial H}{\partial t} + V \frac{\partial H}{\partial x} - V \sin \alpha + \frac{a^2}{g} \frac{\partial V}{\partial x} = 0
\end{equation}

Where $A$ is the cross area of the pipe, $\alpha$ is included angle between the pipe center line and level line, $g$ is the gravitational acceleration, $V$ is the water flow velocity, $x$ is the distance, $H$ is the water...
head, $f$ is the frictional resistant coefficient, $a$ is the water hammer wave velocity, $D$ is the inner diameter of the pipe, $t$ is the time.

Characteristic equations:

\[ C^+ : H_p = C_p - BQ_p \]
\[ C^- : H_p = C_M + BQ_p \]  

Where:

\[ C_p = H_A + BQ_A - R |Q_A| Q_A \]  
\[ C_M = H_B - BQ_B - R |Q_B| Q_B \]  
\[ B = \frac{a}{gA} \]  
\[ R = \frac{fA}{2gDA^2} \]

Where $H_A$ is the water head at the “$i - 1$” point at the “$t - \Delta t$” time point, $H_B$ is the water head at the “$i + 1$” point at the “$t - \Delta t$” time point, $Q_A$ is the water flow at the “$i - 1$” point at the “$t - \Delta t$” time point, $Q_B$ is the water flow at the “$i + 1$” point at the “$t - \Delta t$” time point, $\Delta x$ is the distance between the two points, $R$ is the resistance coefficient, $C_p$, $C_M$ are both related with the water head and flow, and are both known at the “$t$” time point.

2.2.1. The upstream reservoir boundary equation

\[ H_p = H_R - (1 \pm \xi) \frac{Q_p^2}{2gA^2} \]  

In the formula: $\xi$ is the head loss coefficient of the inlet resistance. "+" is taken when the water flow is flowing downstream, and "-" is taken when the water flow is flowing upstream.

2.2.2. Boundary equation of upstream surge chamber

\[ Z_1 = H_{ps1} - k_1Q_{s1}^2 \]  

In the formula: $Q_{s1}$ is the flow into the upstream surge chamber; $Z_1$ is the water level of the upstream surge chamber; $k_1$ is the local loss coefficient of the head when the water flows into the upstream surge chamber, and the outflow and inflow values are different; $F_1$ is the cross-sectional area of the upstream surge chamber. Subscripts 1 and 2 denote tunnel and pipeline parameters, respectively.

2.2.3. Boundary equation of downstream surge chamber

\[ Z_2 = H_{ps2} - k_2Q_{s2}^2 \]  

2.2.4. Turbine boundary equation

\[ \frac{d\omega}{dt} = \frac{1}{J}(M_t - M_\gamma) \]  
\[ M_t = M_1 \cdot D_1^3 H\eta_p/\eta_M \]  
\[ \omega = 2\pi n \]

2.2.5. Boundary equation of tailwater tunnel

\[ H_p = H_R - (1 + \alpha)Q_p^2 / (2gA^2) \]
\[ C^+ : H_p = C_{ps} - B_S \cdot Q_p \]  

2.2.6. Governor transfer function

\[ G(s) = \frac{1 + T_y S}{T_y T_p S^2 + [T_y + T_y b_y] S + b_y} \cdot \frac{1 + T_p S}{1 + K_n T_p S} \]  

Where: \( T_y \) is the reaction time of the guide vane servomotor; \( T_p \) is the buffer time constant of the governor; \( b_y \) is the transient slip coefficient of the governor; \( \gamma \) is the relative value of the travel of the guide vane servomotor; \( \sigma \) is the relative value of the main pressure valve travel; \( T_n \) is the differential time constant of the governor; \( K_n \) is the proportional coefficient; \( \xi \) is the relative deviation of the transient feedback output; \( x \) is the relative deviation of the speed; \( \gamma \) is the relative deviation of the output.

3. Example calculation

3.1. Project Overview

The diversion tunnel of a hydropower station has a length of 6902.66m and an inner diameter of 11.0m, and it adopts full-section reinforced concrete lining. The maximum roughness of reinforced concrete lining is 0.016, the minimum roughness is 0.012, and the average roughness is 0.014. The inner diameter of the pressure pipe is 5.3m, the length of the 1# pressure pipe is 519.064m, the length of the 2# pressure pipe is 504.067m, the length of the 3# pressure pipe is 499.832m, and the roughness of the steel pipe is 0.012. The local head loss coefficient is determined according to the layout of the diversion system. The upstream surge chamber is in the form of a long corridor impedance. The initial diameter of the impedance orifice is 3.0m, and the designed net area of the surge chamber is 737.10m². The downstream tail water surge chamber is also a corridor-shaped impedance type. The initial diameter of the impedance orifice is 3.2m, and the designed net area of the downstream tail water surge chamber is 600.40m². The normal water storage level of the reservoir is 2920.00m, the extraordinary flood level of the reservoir is 2922.71m, the dead water level of the reservoir is 2918.00m, the normal tail water level of the plant is 2698.01m, the lowest tail water level of the plant is 2687.06m, and the normal operation flood level is 2694.44m. The flood level is 2694.97m.

3.2. Stable calculation of small fluctuations

According to the parameters of the diversion power generation system of the hydropower station, according to the calculation formula of the critical area of the Toma section [13-15], the critical stable cross-sectional area of the upstream surge chamber is 288.43m², and the critical stable cross-sectional area of the tailwater surge chamber is 247.83m². Under the condition that the normal water storage level is unchanged and the load fluctuates by 5%, 5 different upstream and downstream surge chamber cross-sectional areas are selected. According to the stability conditions of Thomas, the small water fluctuations of different water level changes in the upstream and downstream surge chambers are calculated. The calculation results are shown in Table 1, Table 2 and Figures 6~12, respectively. In the figure, (a) upstream surge chamber, (b) downstream surge chamber and (c) speed change.

| Table 1. Speed calculation results of small fluctuations in the cross-sectional area of different surge chambers at a normal water storage level of 2920.00m. |
|-------------------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Upstream surge chamber area (m²) | Downstream surge chamber area (m²) | stability | Maximum speed (r/min) | Extreme value appearing time (s) | Overshoot ±0.4%Adjustment time (s) |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 230.00                          | 110.00          | Unstable        | --              | --              | --              |
| 288.43                          | 247.83          | stable          | 217.63          | 4.86            | 1.55%           | 53.92           |
| 500.00                          | 450.00          | stable          | 217.61          | 4.74            | 1.54%           | 42.76           |
Table 2. Calculated water level results of small fluctuations in the cross-sectional area of different surge chambers at a normal water storage level of 2920.00 m^2.

| Upstream surge chamber area (m²) | Downstream surge chamber area (m²) | Stability | Maximum water level of upstream surge chamber (m) | Minimum water level of upstream surge chamber (m) | Attenuation rate of upstream surge chamber | Maximum water level of downstream surge chamber (m) | Minimum water level of downstream surge chamber (m) | Attenuation rate of downstream surge chamber |
|----------------------------------|------------------------------------|-----------|------------------------------------------|------------------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|
| 230.00                           | 110.00                             | Unstable  | --                                       | --                                       | --                            | --                            | --                            | --                            |
| 288.43                           | 247.83                             | stable    | 2916.11                                 | 2911.22                                 | 1.00014                      | 2692.12                      | 2689.81                      | 1.00006                      |
| 500.00                           | 450.00                             | stable    | 2915.20                                 | 2912.28                                 | 1.00026                      | 2691.79                      | 2690.17                      | 1.00008                      |
| 737.10                           | 600.40                             | stable    | 2914.74                                 | 2912.73                                 | 1.00026                      | 2691.58                      | 2690.41                      | 1.00008                      |
| 950.00                           | 800.00                             | stable    | 2914.50                                 | 2912.82                                 | 1.00024                      | 2691.58                      | 2690.41                      | 1.00008                      |

Figure 2. The area of the upstream surge chamber is 230.00 m², and the area of the downstream surge chamber is 110.00 m².
Figure 3. The area of the upstream surge chamber is $288.43 \text{ m}^2$, and the area of the downstream surge chamber is $247.83 \text{ m}^2$.

Figure 4. The area of the upstream surge chamber is $500 \text{ m}^2$, and the area of the downstream surge chamber is $450 \text{ m}^2$. 
According to the analysis of Figures 2~5: The surge chamber is selected to have a smaller cross-sectional area than Toma's stable cross section, and the diversion and power generation system can also be stabilized. When the cross-sectional area of the upstream surge chamber is as small as 230 m² and the cross-sectional area of the downstream surge chamber is as small as about 110 m², the diversion and power generation system begins to become unstable, and the water level fluctuations in the upstream and downstream surge chambers diverge. When the cross-sectional area of the upstream and downstream surge chambers is the calculated critical stable cross-sectional area, the diversion and power generation system is stable, the maximum overshoot of the speed is 1.55%, the adjustment time of ±0.4% is 53.92 seconds, and the attenuation rate of the water level fluctuation of the upstream surge chamber is 1.00014, and the attenuation rate of the water level fluctuation of the downstream surge chamber is 1.00006. At this time, the small fluctuation of the diversion system is stable, but the adjustment time is longer, the attenuation is slower, and the adjustment quality is not good; When the cross-sectional areas of the upstream and downstream surge chambers are respectively designed, the maximum overshoot of the speed is 1.54%, the adjustment time of ±0.4% is 30.26 seconds, the attenuation rate of the water level fluctuation of the upstream surge chamber is 1.00014, and the attenuation rate of the water level fluctuation of the downstream surge chamber is 1.00008. At this time, the diversion power generation system has small fluctuations, stable adjustment time, short attenuation rate, and good adjustment quality; When the area of the upstream and downstream surge chambers was further increased, the adjustment time did not decrease significantly, the attenuation rate remained basically unchanged, and the adjustment quality did not increase significantly.

4. Conclusion

(1) When designing a hydropower station with upstream and downstream dual surge chamber systems, the requirements of the small fluctuation stability of the diversion system on the cross-sectional area of the surge chamber should be considered. Under normal circumstances, the total cross-sectional area of the upstream and downstream surge chamber stability requirements will be greater than the sum of the single upstream surge chamber and single downstream surge chamber stability requirements.

(2) In the diversion power generation system with dual upstream and downstream surge chambers, the water level in the upstream surge chamber first rises while the water level in the tail surge chamber drops first before fluctuating in their respective fluctuation cycles. Correspondingly, under load-increasing conditions, the water level of the upstream surge chamber first decreases, while the water level of the tail surge chamber first rises, and then fluctuates with their respective fluctuation cycles. In the diversion power generation system with dual upstream and downstream surge chambers, the fluctuation periods of the upstream and downstream surge chambers must avoid the similar fluctuation periods to avoid resonance.

(3) The diversion power generation system with dual upstream and downstream surge chambers, the stable cross-section of the surge chamber is larger than that of the single surge chamber system. In fact, the cross-section of the surge chamber of the double surge chamber system uses a smaller area.
than the theoretically derived stable cross-section. The diversion and power generation system may also tend to be stable, but the quality of the regulation is often not ideal. It must be calculated through the transition process of multiple schemes. Combined with economic analysis, a reasonable cross-sectional area of the surge chamber is obtained.

References

[1] Chen Hao. Calculation and research on the hydraulic transition process of the diversion power generation system of the upstream and downstream double surge chambers of the hydropower station [D]. Sichuan University, 2002.
[2] Song Donghui. Stability analysis of water level fluctuations in upstream and downstream dual surge chamber systems [J]. Journal of Hydraulic Engineering, 1996(5): 57-60.
[3] Li Zhenxuan, Ju Xiaoming, Chen Yunliang, Zhang Yurun. Calculation and analysis of small fluctuation stability of upstream series double surge chamber system [J]. People’s Yellow River, 2015, 37(3): 103-106.
[4] Chen Jiayuan. Mathematical simulation and control of hydraulic transition process [M]. 1st edition. Chengdu: Sichuan University Press, 2008.
[5] YANG Kai-lin. The study of hydraulic transient in hydropower station and pumping plant[M]. Beijing: China Water Power Press, 2000, 122-131 (in Chinese).
[6] HEN Jiang-lin, LV Hong-Xing, SHI Xi, ZHU De-Lan, WANG Wen-E. Analysis of Water Hammer Process of Tee Pipe Considering Local Head Loss by Using Characteristic Line Method[J]. Water Saving Irrigation, 2011(10): 17-20 (in Chinese).
[7] WANG Chao, YANG Jian-dong. Solution for short pipe problem in calculation of unsteady flow with Characteristic Line Method[J]. Water Resources and Power, 2013,31(7):77-80 (in Chinese).
[8] Chen Taiping. Analysis and research on the stability of small fluctuations during the transition of hydropower stations [J]. Dongfang Electric Review, 2004, 40(3): 125-128.
[9] Liu Dakai. Water turbine [M]. 3rd edition. Beijing: China Water Resources Press, 1997.
[10] ZHENG Yuan, JU Xiao-ming, CHENG Yun-shan. Water turbine[M]. Beijing: China Water Power Press, 2007 (in Chinese).
[11] PENG Xiao-dong, LIU Shan-jun, JU Xiao-ming, YANG Zhao-hui. Equivalent pipe algorithm for metal spiral casing and its application in hydraulic transient computation based on equiangular spiral model[J]. Journal of Hydrodynamics, 2014, 26(1): 137-143.
[12] Wei Shouping. Turbine adjustment [M]. 1st edition. Wuhan: Huazhong University of Science and Technology Press, 2009.
[13] GUO Wen-cheng, YANG Jian-dong. Research on critical stable sectional area of surge chamber considering the fluid inertia in the penstock and characteristics of governor[J]. Journal of Hydroelectric Engineering, 2014,33(3):171-178 (in Chinese).
[14] LIU Qi-zhao, PENG Shou-zhuo. Surge tank of hydropower station[M]. Beijing: China Water Power Press, 1995 (in Chinese).
[15] Ministry of Electric Power Industry. DL/T 5058-1996 Design Specification for Surge Chamber of Hydropower Station [D]. Beijing: China Water Resources and Hydropower Press, 1996.