Effects of pipe diameters on the pressures during delayed load rejection in high-head pumped storage power stations

W Zeng, J D Yang
State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072

E-mail: wzeng@whu.edu.cn

Abstract. High-head pumped storage power stations face serious problems related to the transient process, especially in the area of delayed load rejection in stations with annular piping layouts. The controlled pressures are adversely affected, which leads to many problems in the engineering design phase. In this study, we investigated this condition through theoretical analysis, numerical simulation, and actual engineering practice. We concluded that the root cause of the pressure issues is the flow switching resulted from the non-synchronous changes in pressure between each branch pipe. Moreover, we examined the impact of the diameters of the upstream main pipe and branch pipe on the controlled pressures and determined that the diameter of the branch pipe has a major influence on the pressures as it changes the flow switching rate. A similar investigation was conducted for downstream pipes. Our conclusions can be applied to actual engineering practice for high-head pumped storage power stations.

1. Introduction

Over the last few years, China has seen the construction of several high-head pumped storage stations to satisfy the increasing demand for electrical power balance and frequency control. Appropriate handling of the hydraulic transient is important to ensure the safe operation of these stations. In terms of the cost of the engineering design, an annular layout is generally adopted for the piping system of a pumped storage station with a high-head and long-distance water conveyance system. However, when the station applies delayed load rejection (DLR), where one of the pump turbines sharing one main pipe rejects its load at a delayed time than other pump-turbines, there may be an extremely low pressure in the draft tube (PDT) and a hazardous pressure in the spiral case (PSC).

To gain an in-depth understanding of the phenomenon and its influence on water hammer, some relevant but limited research has been undertaken. Zhang (2008), who attempted to interpret the phenomenon, discussed the influence of different pipe layouts on the controlled pressures. Zhang (2011) focused on the most dangerous period within DLR for those stations with an annular layout. Fang and Jiri (2012) undertook an investigation on improving the extremely dangerous PDT, through asynchronous guide vane closing, stepped closing of the spherical valve, and modification of the pump-turbine characteristics. These methods have been generally adopted to resolve conflicts with the synchronized load rejection (SLR).

In this paper, we propose a further interpretation of the mechanism of the DLR and an engineering measure aimed at resolving the contradictions presented by this condition. By applying the rigid water hammer theory (Krivchenko 1981), we can derive theoretical formulae for the PSC and
PDT, from which we can conclude that the major influences on the controlled pressures are the inertia time constant of the pipes and the discharge sequence of the pump turbines. By applying theoretical analyses and numerical simulations, we can see that the inertia time constant of the branch pipe has a greater influence than that of the main pipe. The design of the water conveyance system of the ‘Yang Jiang’ pumped storage station verifies this conclusion. Thus, when the regulation guarantee of a pumped storage station cannot satisfy the requirements, the sizes of the branch pipes, rather than those of the main pipes, can be optimized to reduce the cost of a project.

2. Analytical formulae for the PSC and PDT

To discuss the essence of the issue and to facilitate a theoretical derivation, the piping system shown in Fig.1 was established, and the following assumptions were made for the mathematical model. (1) The water hammer in the pipes is rigid. The values of the pressures may be altered based on the assumption, but the trends and laws governing the pressures will not change. (2) The discharge sequences in the turbine are determined by numerical simulation considering the flow characteristics of the pump turbine and the law governing the closing of the guide vanes.

![Figure 1. Generalized model](image)

The Bernoulli equation for the section from the upstream reservoir (1-1) to the inlet of the pump turbine (2-2) can be written as

$$Z_1 = Z_2 + \frac{P_1}{\gamma} + \frac{\alpha_2 Q_2^2}{2gA_{1z}^2} + \frac{L_2}{gA_1} \frac{dQ_1}{dt} + \frac{L_3}{gA_1} \frac{dQ_3}{dt} + \Delta h_{b,2}$$  \hspace{1cm} (1)

For the upstream pipes, the continuity equation is given as

$$Q_1 = Q_2 + Q_3$$  \hspace{1cm} (2)

From the outlet of the pump turbine (2'-2') to the surge chamber (4-4), assuming the piezometric heads on both sides of the surge-chamber to be equal, we obtain

$$Z_2 + \frac{P_2}{\gamma} + \frac{\alpha_2 Q_2^2}{2gA_{2z}^2} = Z_4 + \frac{P_4}{\gamma} + \frac{\alpha_4 Q_4^2}{2gA_{4z}^2} + \frac{L_4}{gA_4} \frac{dQ_4}{dt} + \frac{L_5}{gA_5} \frac{dQ_5}{dt} + \Delta h_{b,4}$$  \hspace{1cm} (3)

The basic equations for the throttled surge chamber are

$$Z_4 + \frac{P_4}{\gamma} = Z_T + \alpha_T Q_T |Q_T|$$  \hspace{1cm} (4)

$$Q_T = F \frac{dZ_T}{dt}$$  \hspace{1cm} (5)

where the water level $Z_T$ in the surge chamber can be determined from the basic equations and the Bernoulli equation for the tailrace tunnel (Yang et al. 2007; Bao et al. 2010). The associated calculation equation is given as

$$\frac{L_T F}{gA_T} \frac{d^2 Z_T}{dt^2} + \alpha_T F^2 \frac{dZ_T}{dt} \frac{d^2 Z_T}{dt} + \alpha_T F Q_T \frac{dZ_T}{dt} + Z_T = Z_5 + \frac{\alpha_4 Q_4^2}{2gA_{4z}^2} + \frac{L_6}{gA_6} \frac{dQ_6}{dt} + \Delta h_{b,4-5}$$  \hspace{1cm} (6)

Substituting Eq. (1) into Eq. (2), we obtain the following expression for the PSC of the turbine (2#):

$$\frac{P_2}{\gamma} = Z_2 - Z_1 - \frac{\alpha_2 Q_2^2}{2gA_{1z}^2} - \frac{L_2}{gA_1} \frac{dQ_1}{dt} - \frac{L_4}{gA_4} \frac{dQ_4}{dt} - \Delta h_{b,2}$$  \hspace{1cm} (7)
In a similar way, inserting the basic equations for the throttled surge chamber into Eq. (3) yields an expression for PDT for the turbine (2#):

\[ \frac{P_t}{\gamma} = Z_t - Z_s + \alpha_i F^2 \frac{dZ_t}{dt} \left| \frac{dZ_t}{dt} \right| + \left( \frac{\alpha_i Q_i^2}{2gA_s} - \frac{\alpha_i Q_i^2}{2gA_s} \right) + \frac{L_i}{gA_s} \frac{dQ_i}{dt} + \frac{L_s}{gA_s} \frac{dQ_s}{dt} + \Delta h_{i-j} \]  

(8)

where \( \gamma \) is the unit weight of water (N/m³); \( g \) is the gravitational acceleration (m/s²); \( \alpha_i \) is the hydraulic resistance coefficient of the flow into or out of the surge chamber (s²/m⁵); \( \alpha_i \) is the kinetic energy correction coefficient; \( Q_i \) is the discharge (m³/s); \( L_i \) is the length of the pipe (m); \( A_i \) is the cross-sectional area of the pipe (m²); \( F \) is the area of the surge chamber (m²); \( P_i \) is the intensity of the pressure for the cross section (i-i) (pa); \( Z_i \) is the height (m); and \( \Delta h_{i-j} \) is the hydraulic loss between section (i-i) and section (j-j) (m).

From Eq. (7), we can conclude that the PSC is associated with not only the flow characteristics of the corresponding pump turbine but also the characteristics of the other pump turbines sharing the same main pipe. Eq. (8) demonstrates that the PDT is determined by the water level in the surge chamber and the water hammer in the tail pipe, which consists of the downstream branch pipes and main pipe upstream of the surge chamber. The downstream surge chamber, however, is close to the bifurcation, which means that \( L_i / A_i \) in Eq. (8) is for a small value. Therefore, there is only a weak association between PDT and the flow characteristics of the other pump turbines.

3. Numerical simulation analysis of DLR

3.1. Simulation model

In studies of the transient process of a hydropower station, the hydraulic system is generally regarded as featuring a one-dimensional compressible unsteady flow. By assuming uniform pressure and velocity distributions across the cross section and neglecting the convective terms, the one-dimensional momentum and continuity balance equations for an elementary pipe filled with water of length \( dl \), cross-sectional area \( A \), and wave speed \( a \), yield the following set of hyperbolic partial differential equations:

\[ \frac{gA^2}{\gamma} \frac{\partial P}{\partial l} + Q \frac{\partial Q}{\partial l} + A \frac{\partial Q}{\partial t} + \frac{fQ|Q|}{2D} = 0 \]  

(9)

\[ \frac{Q}{\gamma} \frac{\partial P}{\partial l} + A \frac{\partial P}{\partial l} + \frac{a^2}{g} \frac{\partial Q}{\partial l} = 0 \]  

(10)

Eqs. (9) and (10) form the quasilinear hyperbolic partial differential equation group, which can be transformed into two sets of ordinary differential equations through the application of the characteristic method. By integrating along the characteristic direction, we can obtain the pressures and discharges in the transient system.

3.2. Mechanism of the DLR

The generalized model shown in Fig.1 was adopted to analyse the mechanism of the DLR. Pipe friction was not taken into account. The net head is 700 m, the rated flow is 67.60 m³/s, the rotational speed is 500 rpm, the guide vanes close in 30 s, the 1# turbine is the first to reject the load, and the 2# turbine rejects the load at 3-s intervals. The pipe parameters are listed in Table 1, and the branch pipes are symmetrical.

| Pipe order | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|------------|-----|-----|-----|-----|-----|-----|-----|
| Length (m) | 1500| 200 | 200 | 150 | 150 | 20  | 1000|
| Diameter (m) | 7.4 | 3.5 | 3.5 | 4.3 | 4.3 | 7.4 | 7.4 |

The PSC and PDT are directly related to the discharge sequences shown in Fig.2. Through these analyses, we can draw the following conclusions:
(1) The pressure at the bifurcation increases upon load rejection by the 1# unit, and this leads to an increase in the initial flow of the 2# unit upon DLR at 3 s. However, the increase in the amplitude is small, so this may not be the dominant reason for the dramatic change in the PSC and PDT.

(2) The flow in the 1# unit falls during the period between 3 and 6 s, and the decrease in the gradient of the flow in the 2# unit is relatively small. Therefore, we can see that the flow switching between the branch pipes is not clear during this period. From 6 to 8.5 s, the flow increases dramatically in the 1# unit, and decreases sharply in the 2# unit. Meanwhile, the flow falls in the 2# unit, but increases in the 2# unit between 8.5 and 10 s. Thus, the flow switching is distinct. The upstream manifold can distribute the total flow to the branch pipes, as well as serving as a connector for the flow switching between the branch pipes, as shown in Fig.3. Here, the point at which the fluid begins to oscillate (6 s) is defined as the start point and that at which the direction of the oscillation changes (8.5 s) is defined as the turning point. The interval between the two points is $T_s$, which is half a cycle of the flow switching as shown in Fig.4. The extremes of the PSC and PDT values occurred within this interval regardless of the size of the pipes constituting the water conveyance system. The start point and the discharge at the turning point remain constant, so we define the semi-period $T_s$ as representing the average flow gradient in the 2# unit. Furthermore, a larger $T_s$ value is associated with a smaller average flow gradient.

(3) Ignoring any hydraulic loss, the Bernoulli equation for section 2-2 to section 3-3 is

$$
\frac{P_2}{\gamma} + \frac{\alpha_1 Q_2^2}{2gA_2} + \frac{L_2}{gA_2}, \frac{dQ_2}{dt} = \frac{P_1}{\gamma} + \frac{\alpha_2 Q_2^2}{2gA_2} + \frac{L_1}{gA_2}, \frac{dQ_1}{dt}
$$

Neglecting the velocity head gives

$$
\frac{d(Q_2 - Q_1)}{dt} = \frac{gA_1}{L_2} \cdot \frac{P_1 - P_3}{\gamma}
$$

where the switched discharge is expressed as $(Q_2 - Q_1)/2$. When the two units are independent of each other during DLR, there will be a periodic pressure change only for the start time difference, as shown in Fig.4 (a). However, the two units interact through the manifold, so that the periodic change in the pressure difference is bound to affect the rate of change of the switched discharge given by Eq. (12). Meanwhile, the rate of change of the discharge will affect the PSC. This ultimately gives rise to the pressure difference and discharge difference traces corresponding to Eq. (12), as shown in Fig.4 (b). We can say, therefore, that the root cause of the flow switching between the branch pipes is the pressures in the pipes not changing synchronously with each other, which results in a periodic discharge difference between the connecting pipes.

![Figure 2](image1.png)

**Figure 2.** Discharge processes during DLR and SLR

![Figure 3](image2.png)

**Figure 3.** Flow switching in manifold
The PSC and PDT during DLR, as shown in Fig.5, contrast with the pressure sequences during SLR. The more hazardous pressures during DLR can be seen in this figure.

The flows in the branch pipes are not synchronized during DLR, as shown in Fig.2. The maximum PSC is associated with the flows in the upstream main pipe and branch pipes. In terms of the flow in the main pipe, the total closing time of the guide vanes increases during the DLR because the closing of the guide vanes in one of the pump turbines is delayed, thus reducing the flow gradient in the main pipe. For the branch pipes, however, the flow rapidly declines in the unit that subsequently performs rejection (2#) due to the flow switching between the two units during DLR. Equation (7) shows that the levels of the main and branch pipes affecting the maximum PSC are related to \( L_1/A_1 \) and \( L_2/A_2 \). Especially, when \( L_1 \) is large, the maximum pressure is greatly affected by the flow gradient in the main pipe, so does not notably exceed the pressure during SLR. In addition, when \( L_2 \) is small, the main effect stems from the flow gradient in the branch pipes, so the pressure may be markedly higher than that during SLR. In Table 2, we compare the rate at which the maximum pressures rise during DLR at the most adverse rejection interval with that during DLR for different lengths of the main pipe, and conclude that the relatively higher rate of pressure increase, namely \((DLR - SLR)/SLR\), is positively correlated to the length.

Table 2 Comparison of rate of rise of maximum PSC during DLR and SLR

| \( L_1 \) (m) | 1500 | 1750 | 2000 | 2250 | 2500 |
|---------------|------|------|------|------|------|
| DLR (%)       | 25.52| 26.77| 28.11| 29.26| 29.75|
| SLR (%)       | 23.61| 25.18| 26.65| 28.05| 29.16|
| \( (DLR - SLR)/SLR \) (%) | 8.09 | 6.32 | 5.48 | 4.34 | 2.03 |

From Equation (6), we can conclude that the water level in the surge chamber mainly depends on the tail system, and is basically the same during both DLR and SLR. Therefore, the main factor
leading to the sharp decline in the minimum PDT is the discharge sequence of the corresponding unit, which falls sharply due to the flow switching during DLR.

4. Effect of pipe diameters on DLR

4.1. Upstream pipes

The PSC and PDT are directly related to the sizes of the branch pipes and the main pipes, which are represented by \( L/A \) in Equations (7) and (8). In practical projects, the lengths of the pipes usually cannot be changed by any significant amount due to the restrictions imposed by the topography and geology. As a result, therefore, we chose to focus on the influence of the cross-sectional areas of the pipe.

After reducing the diameter of the upstream branch pipe from 3.5 to 3.0 m over 0.1 m, while keeping the other parameters constant, the PSC and PDT can be determined by numerical simulation. The controlled pressures are listed in Table 3, and the discharge sequences during a given period are shown in Fig.6(a). To contrast with the influence of the upstream main pipe, we changed its diameter as shown in Table 4 to maintain \( 2L/A_1 + L/A_2 \) corresponding to the schemes for changing the branch pipes, that is, to maintain the correspondence with the inertia time constant \( T_w \) in the upstream pipes. The controlled pressures are listed in Table 4, and the discharge sequences are shown in Fig.6(b).

![Discharge sequences for different upstream pipe diameters](image)

**Figure 6.** Discharge sequences for different upstream pipe diameters

| Diameter of branch pipe (m) | 3.50 | 3.40 | 3.30 | 3.20 | 3.10 | 3.00 |
|-----------------------------|------|------|------|------|------|------|
| Maximum PSC (m)             | 998.55 | 999.56 | 1000.59 | 1002.61 | 1005.54 | 1010.45 |
| Minimum PDT (m)             | 14.34 | 15.72 | 18.96 | 21.46 | 23.69 | 26.71 |

| Diameter of main pipe (m)   | 7.40 | 7.34 | 7.27 | 7.19 | 7.11 | 7.03 |
|-----------------------------|------|------|------|------|------|------|
| Maximum PSC (m)             | 998.55 | 999.27 | 1001.59 | 1002.13 | 1003.81 | 1005.28 |
| Minimum PDT (m)             | 14.34 | 14.64 | 14.73 | 15.25 | 15.17 | 15.49 |

After changing the diameter of the upstream branch pipe, the total discharge \( Q_1 \) is barely affected, as this is mainly determined by the closing of the guide vanes and the pump-turbine flow characteristics. Meanwhile, the turbine discharges \( Q_2 \) and \( Q_3 \) change with the diameter because the rate of the flow switching is affected by the pipe size. Integrating the differential equation (10), we obtain the formula for the switched discharge:

\[
\frac{(Q_2 - Q_1)}{2} = \frac{gA_2}{2L_2} \int_{t_0}^{t} \frac{P_1 - P_2}{\gamma} dt
\]

(13)

where \( t_0 \) is the start time (6 s), and \( t \) is the time from the start point to the turning point (6 to 8.5 s). \( A_2 \) apparently influences the switched discharge, so that the switched discharge, flowing from the 2#
turbine into the 1# turbine, declines at time $t$ with a reduction in the diameter. Thus, the discharge at this time increases, and the average discharge gradient for the 2# pump turbine decreases, illustrated by the increase in $T_s$, as shown in Fig.6(a). Through Equations (7) (8) and the analysis above, we can conclude that, when the diameter of the branch pipe decreases, the PDT of turbine 2# will rise in response to a change in $|dQ_1/dt|$, and the PSC will increase with a rise in $T_w$.

With different main pipes but the same branch pipes, the total discharge $Q_1$ changes only slightly, and the flow switching rate remains the same, leading to a sequence whereby the turbine discharge $Q_2$ remains near-constant. Thus, when the diameter of the main pipe is reduced, the PDT of turbine 2# will not change as the average $|dQ_2/dt|$ changes slightly, although the PSC increases with $T_w$.

A sensitivity analysis of the upstream pipes lets us conclude that the diameter of the upstream branch pipe has a greater influence than that of the main pipe, particularly on the PSC.

### 4.2. Upstream pipes

Increasing the diameter of the downstream branch pipe from 4.3 to 5.3 m over 0.2 m, while keeping the other parameters as is, results in the controlled pressures being as listed in Table 5, with the discharge sequences being as shown in Fig.7(a). Changing the diameter of the downstream main pipe to keep the inertia time $T_w$ constant in those downstream pipes corresponding to the schemes for changing the branch pipes gives the controlled pressures listed in Table 6 and the flow processes shown in Fig.7(b).

![Figure 7. Discharge sequences for different downstream pipe diameters](image)

Table 5 | Controlled pressures for different downstream branch pipe diameters
| Diameter of branch pipe (m) | 4.30 | 4.40 | 4.50 | 4.60 | 4.70 | 4.80 |
|-----------------------------|-----|-----|-----|-----|-----|-----|
| Maximum PSC (m)            | 998.55 | 1000.19 | 1003.02 | 1005.47 | 1006.92 | 1008.17 |
| Minimum PDT (m)            | 14.34 | 16.88 | 19.34 | 21.48 | 22.91 | 24.25 |

Table 6 | Controlled pressures for different downstream main pipe diameters
| Diameter of main pipe (m)  | 7.40 | 7.47 | 7.53 | 7.59 | 7.64 | 7.69 |
|---------------------------|-----|-----|-----|-----|-----|-----|
| Maximum PSC (m)           | 998.55 | 997.51 | 997.50 | 997.50 | 997.50 | 997.49 |
| Minimum PDT (m)           | 14.34 | 14.36 | 14.37 | 14.37 | 14.37 | 14.38 |

Changing the diameter of the downstream branch pipe causes the discharge $Q_1$ in the downstream main pipe before the surge chamber to change only slightly, while the turbine discharge $Q_2$ changes considerably. Similarly to the analysis of the upstream pipes, increasing the diameter of the downstream branch pipes causes the flow switching rate to decline, which leads to a decrease in the average discharge gradient in the 2# pump turbine, as $T_s$ increases as shown in Fig.7(a). Thus, when the diameter of the downstream branch pipe increases, the PSC of the 2# turbine will rise with an increase in the average of $|dQ_2/dt|$, and the PDT will increase with $T_w$.

In order to satisfy the requirements of the regulation guarantee of pumped storage stations, the area of the surge chamber must be considerably larger than the Thomas critical stable section area,
such that the surge chamber can be regarded as just being a small reservoir. When the water hammer wave reaches the surge chamber, it will be largely reflected. Because of this, the downstream main pipe after the surge chamber has little influence on the hydraulic transient in the piping system. Meanwhile, the turbine discharge will not change with any increase in the diameter of the downstream main pipe, as shown in Fig.7(b), and the water level in the surge chamber changes very little in the earlier process of load rejection, as shown in Fig.8. Thus, from Equations (7) and (8), we can conclude that the PSC and PDT will not change.

![Figure 8. Water levels in surge chamber for different downstream main pipe diameters](image)

In conclusion, we can say that the diameter of the downstream branch pipe is closely related to the PSC and PDT, but the diameter of the main pipe is independent of these pressures when a surge chamber is configured in the downstream main pipe.

5. Engineering practice

To verify the conclusion proposed herein, we examined the ‘Yang River’ pumped storage station as an engineering case. The annular layout, with three pump turbines sharing one main pipe, was adopted to cut costs. One surge chamber is provided in the downstream main pipe. The pump turbines are installed at a height of -25 m. The controlled working conditions of the PSC and PDT are described as follows: the upper level is the design flood level of 773.7 m, and the downstream water level is the dead storage water level of 75 m; two of the pump turbines reject their loads, with the last one rejecting its load at 4-s intervals.

The PSC is not the main issue faced by this station because the bearing capacity could be enhanced by strengthening the structure of the pump-turbine inlet pipe. The minimum relative PDT, however, must be held at 2 m. In the simulation, 10% of the pressure increase/decrease was introduced as the calculation error, as well as 7% of the net head in consideration of the pulsation in the spiral case or 3.5% in the draft tube. It follows that this station has a high head and demands a high control standard, and this station respects the development trend observed for pumped storage power stations in China.

In the original plans, the diameters of the upstream branch pipe and downstream branch pipe were 3.5 m and 4.3 m, respectively. Considering the calculation error and the pulse pressure, the minimum PDT is calculated as being -41.13 m, which is significantly less than the control standards, which would cause the pump turbine to suffer serious cavitation in the transient process. By applying our analytical conclusion, we can change the diameters of the branch pipes to transfer the water hammer from downstream to upstream. The relationships between the controlled pressures and the diameters of the branch pipes are shown in Fig.9. This figure clearly shows that reducing the diameter of the upstream branch pipe or increasing that downstream can improve the PDT, but increases the PSC at the same time.
The synthetic measure of modifying the diameter of the upstream branch pipe to 3.0 m, and that of the downstream one to 5.8 m, was adopted. The minimum PDT after this modification was found to be 2.06 m, which is within the control standard.

6. Conclusions

Through theoretical analysis, numerical simulation, and engineering practice, we discussed the mechanism of the DLR in a pumped storage station with an annular layout, which is also the cause of the critical PSC and PDT. Meanwhile, we proposed an engineering measure to improve the PDT by changing the branch pipe diameters. We can draw the following conclusions:

(1) When the station applies a DLR, the discharges in the branch pipes will be transferred to each other; this leads to the flow switching phenomenon. This is due to the periodic pressure difference between the branch pipes, which is caused by unsynchronized load rejections. For water conveyance systems incorporating different diameters of pipes, the flow switching rate will change, which will lead to a change in the flow gradient in the branch pipes.

(2) As a result of the rapid reduction in flow in the pump turbine, the minimum PDT will exhibit a large decline, and the maximum PSC may increase for the same reason, especially when the upstream main pipe is short.

(3) During a DLR of a high-head pumped storage station with an annular piping layout, the diameter of the upstream main pipe has little influence on the PDT, while the pressure is improved as the diameter of the upstream branch pipe is increased. Both upstream pipes are closely related to the PSC; the PDT will be improved and the PSC will increase as the diameter of the downstream branch pipe is increased. When a surge chamber is provided in the downstream main pipe, the diameter of the downstream main pipe will be independent of the PSC and PDT. In actual engineering practice, we can transfer the water hammer by modifying the diameters of the branch pipes to resolve the conflicts presented by the regulation guarantee.

Acknowledgments

This work was supported by the National Natural Science Foundation of China under Grant 51039005.

References

[1] Zhang, J., Lu W. H., Fan B. Q., and Hu, J. Y., 2008. The influence of layout of water conveyance system on the hydraulic transients of pump-turbines load successive rejection in pumped storage station. Journal of hydroelectric engineering, 27(5), 158-162. (In Chinese)

[2] Zhang, C., 2011, Study on transition process of load successive rejection of multiple units per penstock in pumped storage hydropower station. Water resources and hydropower engineering, 42(12), 66-70. (In Chinese)

[3] Fang, Y. J., and Jiri, K., 2012. The numerical simulation of the delayed load rejection of a pump-turbine power plant. 26th IAHR Symposium on Hydraulic Machinery and System,
Beijing, China.

[4] Krivchenko, G. I., 1981, Transient Process of Power Plant in the Hydropower Station, Hydraulic press, Beijing.

[5] Yang, J. D., Zhan, J. J., and Bao, H. Y., 2007. Effect of tailrace surge tank location on adjustment and assurance. Journal of Hydrodynamics, 22(2), 162-167. (In Chinese).

[6] Bao, H. Y., 2010. Research on setting condition of surge camber and operation control of the hydropower station. Ph.D. Thesis. Wuhan University, Wuhan, China.

[7] Li, L., Yang, J. D., 2010. Advanced simulation of hydroelectric transient process with Comsol/Simulink. 25th IAHR Symposium on Hydraulic Machinery and System, Timisoara, Romania.

[8] Pannatier, Y., Nicolet, C., Kawkabani, B., Deniau, J. L., Schwery, A., Avellan, J. F., and Simond, J., 2008. Transient behavior of variable speed pump-turbine unit. 24th IAHR Symposium on Hydraulic Machinery and System, Parana, Brazil.