Study on Selection of Pressure Regulating Valve for Hydropower Station with Both Surge Tank and Pressure Regulating Valve

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Abstract. The transient process in the hydropower station with both surge tank and pressure regulating valve is quite complicated and also critical to operation safety. According to the pressure regulating valve working principle, the influence of the valve diameter on the unit speed and spiral case pressure was analyzed theoretically. Mathematical models of the surge tank and pressure regulating valve in the hydropower station were established based on the characteristic method. In a practical engineering, numerical simulation of large fluctuation and hydraulic disturbance transient process are conducted, verifying the correctness of the theoretical analysis. Based on the calculation results, three principles for selecting the valve diameter are concluded: first, making sure the unit speed meet the regulating guarantee requirements when guide vanes fast close; second, the maximum spiral case pressure of two times should be approximate to each other by controlling the superposition of surge wave and water hammer; third, the maximum flow of the valve should be as close to the rated flow of the turbine as possible. The principles are helpful for selecting the valve diameter in similar hydropower station.

1 Introduction

Load rejection transient process is a frequent occurrence in hydropower station. During the process, to control the unit speed, the guide vanes will close rapidly, which will cause large water hammer pressure in pipelines, threatening the safe operation of the station [1-3]. To reduce the maximum pressure of spiral case ($H_{\max,s}$) and the maximum rising rate of unit speed ($N_{\max,u}$), a surge tank (ST) is often built at the end of pressure headrace tunnel [4-5].

For small hydropower stations, with the topographic and geological condition constraints, pressure regulating valves (PRV) are often used in place of ST and work quite well, such as Longyuan station, Lemonthyme station [6-7]. But for the stations with long-distance water diversion system, the flow inertia time constant is very large, so the small fluctuation may not converge and the hydraulic disturbance will be strong without ST. Moreover, a big ST is hard to excavate because of the difficulty in technology and capital. In this cases, it is preferable to using a small ST to guarantee the small fluctuation stability and to using PRV to further reduce the water hammer pressure and unit speed [8], as shown in Fig. 1.

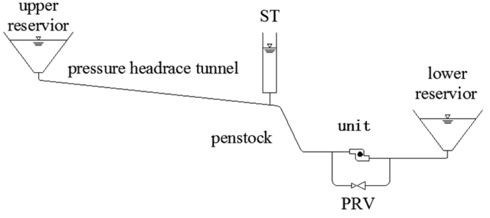

Figure 1. Diagrams of different water conveyance systems.

The transient process of hydropower stations with PRV instead of ST have been studied by many scholars, so empirical formula is available for the diameter selection of PRV [9]. However, for the hydropower station with both ST and PRV, the transient process is much more complex, so there is no empirical formula available and only a few relevant researches [10-11]. In this paper, the influence of PRV diameter on $H_{\max,s}$, $N_{\max,u}$, and the maximum rising rate of unit torque ($T_{\max,u}$) were analyzed theoretically in the load rejection transient process of the hydropower station with both ST and PRV. In a practical engineering project, the opening and closing law of PRV and guide vanes are selected, and the PRV diameter was optimized. Based on the theoretical analysis and numerical simulation results, three principles for selecting the PRV diameter were summarized.

2 Mathematical model

2.1 Basic equations of water hammer

In the hydraulic transient calculation, from the continuity equation and dynamic equation of water flow, the basic equations of water hammer can be deduced as follows:

$$\frac{Q}{A}\frac{\partial H}{\partial x}+\frac{\partial H}{\partial t}+\frac{a^2}{gA}\frac{\partial Q}{\partial x}-\frac{Q}{A}\sin\beta=0 \tag{3}$$

$$g\frac{\partial H}{\partial x}+\frac{Q}{A^2}\frac{\partial Q}{\partial x}+\frac{1}{A}\frac{\partial Q}{\partial t}+\frac{fQ|Q|}{2DA^2}=0 \tag{4}$$

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Where Q and H are the discharge and head in the pipe respectively; A is the cross-sectional area of the pipe; x is the distance along the pipe; t is the time; a is the wave velocity of water hammer; g is the gravitational acceleration; β is the longitudinal slope of the pipe; f is the friction coefficient; D is the pipe diameter.

Leaving out minor items in the basic equations, hyperbolic partial differential equations are obtained, which can be transformed into ordinary differential equations by means of characteristic method. With boundary conditions and initial conditions, pressure and flow during the whole transient process in the pressure conduit can be calculated [12].

2.2 Governing equations of ST

For ST, when the tank bottom is treated as a bifurcated pipe and the nodes before and after the impedance hole are 1 and 2 respectively, the characteristic equations are as follows:

$$H_{P1} = C_P - R_P Q_{P1} \tag{3}$$

$$H_{P2} = C_M + R_M Q_{P2} \tag{4}$$

Where H_{P1}, H_{P2} are the head in node 1, 2; Q_{P1}, Q_{P2} are the flow in node 1, 2; C_M, R_M, C_P, R_P can be obtained from pipe parameters, head and flow before and after the impedance hole in the previous moment.

The continuity equation, dynamic equation and relational expression between water level and discharge of the ST are as follows:

$$Q_{P1} = Q_{st} + Q_{P2} \tag{5}$$

$$H_{P1} = H_{P2} = Z_{st} + R_k Q_{st} \left| Q_{st0} \right| \tag{6}$$

$$\left(Q_{st} + Q_{st0}\right) \mathrm{d}t = 2A_{st}\left(Z_{st} - Z_{st0}\right) \tag{7}$$

Where Q_{st} is the discharge into the ST; A_{st} is the cross-sectional area of the ST; Z_{st} is the water level in the ST; R_k is the water head loss coefficient of the impedance hole.

Solving Eqs. (1) to (5) simultaneously gives Q_{st} and A_{st}.

2.3 Governing equations of PRV

As for PRV, the characteristic equations are as (3) and (4), when the nodes of the inlet and outlet of the PRV are 1 and 2 respectively. The formula reflecting the pressure in the inlet and outlet and the flow of the PRV are as follows:

$$Q_{P1} = Q_{P2} = Q_P \tag{8}$$

$$Q_P = f(\tau) D_x^{\,2} \sqrt{H_{P1} - H_{P2}} \tag{9}$$

Where Q_{st} is the discharge of the PRV; A_{st} is the opening of the PRV; Z_{st} is the diameter of the PRV.

Solving Eqs. (3), (4), (8) and (9) simultaneously results in

$$Q_P = \frac{\Delta H_P f(\tau)^2 D_x^{\,4}}{2} \tag{10}$$

$$\Delta H_P = \sqrt{\left(R_P - R_M\right)^2 + \frac{4\left(C_P - C_M\right)}{f(\tau)^2 D_x^{\,4}}} - R_P - R_M \tag{11}$$

Taking Q_P into Eqs. (3), (4) and (8) gives the H_{P1} and H_{P2}.

3 Selections of PRV

3.1 Working principles of PRV

The PRV is an equipment using for bypass flow usually set on the turbine floor in the hydropower station. Its inlet connects volute and outlet connects draft tube or the downstream. The PRV commonly used in China is the TFW type, whose working principle is: when the unit load increases or remains unchanged, or the load rejection is less than 15% of the rated output, it stays closed; when the instant load rejection is more than 15% of the rated output, it fast opens to discharge flow, and then slowly closes when the guide vanes are completely closed [13].

In the station with PRV, when load rejection happens, the guide vanes fast closes, and in the meantime, the PRV fast opens to discharge some high-pressure water flow in the spiral case into downstream, and then the PRV closes slowly. The discharging function of PRV helps, on one hand, reduce the velocity variation gradient in the conduit therefore lessening the $H_{\max,s}$, and on the other hand reduce the high-pressure water flows through the unit therefore decreasing the $N_{\max,u}$. As a result, the safety of the hydropower station is guaranteed [14].

3.2 Opening and closing law of WG and PRV

With the layout of water conveyance system and rotational inertia of the unit and other variates remain unchanged, optimizing the opening and closing law of guide vanes can decrease the $H_{\max,s}$ and $N_{\max,u}$ during load rejection transient process, which is clearly a simple and productive method[15-16]. In the station where PRV and guide vanes work jointly, the opening and closing law has more complicated influence. Besides, when PRV slowly closes, the change of velocity variation gradient will cause another wave of water hammer pressure. So for the hydropower station with both ST and PRV, the influence of the opening and closing law of guide vanes and PRV should be considered when selecting the PRV.

If the PRV diameter and opening and closing law are optimized at the same time, the variates involved will be so many that the optimal calculation will be too much. For this kind of multi-objective problem with multivariate, it's difficult and unnecessary to solve the optimal solution, just finding out one feasible solution is viable. it means that searching for one combination of PRV diameter and opening and closing law that not only meets the regulating guarantee requirements, but also the safety margin is enough. In practical operation, a certain PRV diameter is chosen first, and the transient process are calculated with different opening and closing laws, the one with the optimal result is selected as the practical opening and closing law, and then with this certain law, the PRV diameter is optimized.

3.3 Analysis of the selection of PRV

During the transient process, the water pressure in the pipeline are the algebraic sum of hydrostatic pressure and water hammer pressure. For the hydropower station with ST, the hydrostatic pressure depends on the ST water level and the water hammer pressure depends on the velocity variation gradient in the conduit.

When all units rejecting load, the guide vanes close and PRV opens quickly, so the flow reduction in the conduit leads to the first wave of pressure rise. The pressure of spiral case and the unit speed reaches their maximum value before the full closure of guide vanes. After that, the PRV closes slowly and the flow in the conduit decreases gradually, and the water in the headrace tunnel therefore flows into ST, causing water level rising in ST. Then, the second wave of pressure rise comes, and the extremum pressure at PRV inlet appears at the moment that PRV fully closes. Based on the PRV characteristics that the larger the PRV diameter, the more the discharge flow, so the greater the influence on unit, the influence caused by the PRV diameter change on $H_{\max,s}$, $N_{\max,u}$ and $T_{\max,u}$ are analyzed as follows:

The influence of PRV diameter on $H_{\max,s}$ in the first wave: the guide vane is fast closed in a very short time, the water ST level changes slightly in the closing process. So the extremum pressure should be decided by the water hammer pressure. The PRV diameter increase will decrease water hammer pressure caused by the guide vanes closing and therefore reduce $H_{\max,s}$ in the first wave.

The influence of PRV diameter on $H_{\max,s}$ in the second wave: firstly, since the discharge flow of PRV with larger diameter is also large, so the water hammer pressure caused by the PRV closing if the PRV diameter increase; secondly, the larger the PRV diameter, the more water it discharges in the same period of time, so the smaller the rising of ST water level and thus the smaller the hydrostatic pressure. From the above, it can be seen that the influence of PRV diameter on $H_{\max,s}$ in the second wave is uncertain, which is different from the station with only PRV.

The influence of PRV diameter on $N_{\max,u}$: with the same discharge volume of the conduit in the same condition, when the unit rejects load, the larger the PRV diameter, the larger its discharge volume, the less the water flowing through guide vanes, so the smaller the $N_{\max,u}$.

The influence of PRV diameter on $T_{\max,u}$: When some units that use one headrace tunnel reject load, guide vanes of the load-rejection turbines close quickly and its PRV fast opens, while the PRV of the normally working turbines remains closed. When PRV diameter is too large that the maximum PRV flow is larger than the rated unit flow, the excess flow will be discharged from PRV and the normally working turbines will be greatly disturbed, and $T_{\max,u}$ will be large. Even worse, if the disturbance is over the protective relaying, units may reject load successively, which will seriously threaten the safety of the hydropower station [17].

Based on the above analysis, when selecting PRV diameter, the large fluctuation condition and hydraulic disturbance condition should be calculated respectively, and the $H_{\max,s}$, $N_{\max,u}$, $T_{\max,u}$ should be considered comprehensively.

4 Case study

4.1 Basic information

In a diversion-type hydropower station, the water diversion system is 7203m of the length, with 6416m of pressure headrace tunnel and 787m of penstock. the station adopts the layout of one headrace tunnel with two big and one small units. The rated head of the units is 158.5m. The rated outputs are 46.55MW and 20.58MW respectively. The rated flows are 31.75 m^3/s and 14.19 m^3/s respectively. The rated speeds are 333.3r/min and 500r/min respectively. The throttled surge tank is set at the end of the pressure headrace tunnel, with a cross section diameter of 16m.

The regulating guarantee requirements are: the $H_{\max,s}$ should be below 214.00m, and the $N_{\max,u}$ should be no higher than 50%. The control condition of the $H_{\max,s}$ and $N_{\max,u}$ is: the upstream water level is the maximum water level(1347.77m), the downstream water level is the design water level(1172.33m), the units work at the 1.1 times rated output, and all turbines reject load simultaneously.

When the ST is adopted and without PRV, the simulation calculation results of the control condition with different closing law of guide vanes are shown in Table 1.

The main consequences of underground pipe burst are as follows: Frist, when the pipe burst occurs, the pressure of the burst point decreases rapidly, leading to a sharp increase in the upstream discharge and a large amount of water gushing out of the ground, which in turn cause serious damage to the surrounding environment. Second, the only measure for water hammer protection is the air vessel, and the air vessel is installed behind the check valve at the upstream end of the pipeline. Because of the pipe sudden burst, the negative pressure wave generated by the pipe burst propagates downstream, and the points where the initial pressures are relatively low along the pipeline may be reduced to the vaporization pressure, thereby causing the new burst points.

Table 1. Simulation calculation results with different closing law of the guide vanes.

Closing law	$H_{\max,s}$ (m) (Big unit / small unit)	$N_{\max,u}$ (%) (Big unit / small unit)
9/7	242.87/243.72	57.28/59.18
10/8	236.00/237.03	58.92/61.90
11/9	229.78/230.68	60.26/63.89

broken-line 1	236.87/237.14	54.40/57.66
broken-line 2	250.79/250.53	63.98/64.21

Note: Broken-line closing law 1: the guide vanes of the big/ small turbine fast close for 2/1s to 0.7 relative opening degree and then slowly close for 8/7s to full closure. Broken-line closing law 2: the guide vanes of the big/ small turbine slowly close for 5/4s to 0.7 relative opening degree, and then fast close for 5/4s to full closure.

It can be seen from Tab.1 that: no matter how to adjust the closing law of the guide vanes, the requirements for $H_{\max,s}$ and $N_{\max,u}$ are not met, so the safe operation of the station cannot be guaranteed by ST alone.

When PRV is adopted and without ST, the small fluctuation of the station may not converge, because the PRV is not work in small fluctuation transient process. The inertia time constant of this hydropower station is 12s, longer than 4s, so whether or not to set a ST should be determined by the hydraulic transient calculation. After theoretical calculation, through the trial calculation of governor parameters by traversing method, the stable region cannot be found. It means that when governor parameters are set within the normal range, the small fluctuation of the system not converge. Therefore, using ST alone cannot make sure the safe operation of the station.

From the above analysis, it can be known that when ST or PRV is adopted alone, the safe operation of the station cannot be guaranteed, so both ST and PRV are adopted to ensure the safety during transient process.

4.2 Optimization of the opening and closing law

The opening and closing law of the guide vanes and PRV should be the first to decide in the selection of PRV. To ensure the reliability of the governor in the linkage of the guide vanes and PRV, linear closing law is usually adopted in practical engineering projects. With the diameter of PRV is 0.9/0.5m, the transient process of control condition is calculated with different opening and closing laws. The calculation results are shown in Table 2:

Table 1. Simulation calculation results with different closing law of the guide vanes.

Opening and closing law	$H_{\max,s}$ (m) (Big / small)	$N_{\max,u}$ (%) (Big / small)
1:8-6-10-120	201.85/200.54	40.40/42.17
2:9-7-10-120	198.47/198.33	43.91/44.64
3:10-8-10-120	197.70/197.77	46.79/46.71
4:11-9-10-120	197.67/197.75	49.15/48.48
5:12-10-10-120	197.66/197.73.	51.13/50.04
6:10-8-10-60	199.05/199.19	46.79/46.71
7:10-8-10-180	196.20/196.10	46.79/46.71
8:10-8-20-120	197.41/197.47	46.79/46.71

Notes: The closing law 8-6-10-120 means that the guide vanes of big/ small unit fast close for 8/6s, while the PRV fast open for 8/6s and fully open for 10s and then slowly close for 120s.

It can be shown from the calculation results of law 1-5 that the closing time of guide vanes has a significant influence on the $T_{\max,u}$, while it has a significant light influence on the $N_{\max,s}$. When the closing time changes from 8/6s to 12/10s, the $N_{\max,s}$ decreases slightly, and all within the required range of the guaranteed calculation for regulation, but the $T_{\max,u}$ rises significantly. When the closing time is over 10/12s, the $T_{\max,u}$ exceed the requirement. So in regard of controlling the $T_{\max,u}$ and leaving some amount of safety margin, the closing time of guide vanes should be 8/10s.

It can be shown from the calculation results of law 3, 6 and 7 that the change of PRV closing time has no influence on the $T_{\max,u}$, because it occurs before the complete closure of guide vanes. If the closing time of guide vanes remains unchanged, it will stays the same. The influence of PRV closing time is mainly on the $N_{\max,s}$ in the second wave caused by the closure of PRV, but the influence is very slight. Therefore, in order to control the $N_{\max,s}$ and reduce water energy loss, the closing time should be 120s.

It can be shown from the calculation results of law 3 and 8 that the fully opening time of PVR has little influence on the $T_{\max,u}$ and $N_{\max,s}$. So in order to water energy loss, the delay time should be 10s.

Based on the above analysis, the closing law 3 of guide vanes-PRV is adopted: guide vanes fast close for 9/7s, while the PRV fast open for 9/7s and fully open for 10s and then slowly close for 120s, as is shown in Figure 2.

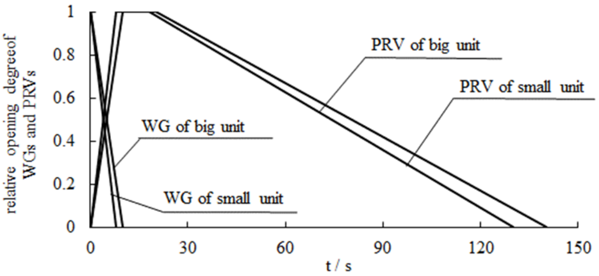

Figure 2. Diagram of the opening and closing law of PRV and guide vanes

4.3 Large fluctuation transient process

With the opening and closing law of guide vanes and PRV determined, five combinations of PRV diameter (for big/ small turbines) are used for simulation calculation, that are 0.7/0.3, 0.8/0.4, 0.9/0.5, 1.0/1.6 and 1.1/0.7m. The calculation results are shown in Figure 3-6 and Table 3.

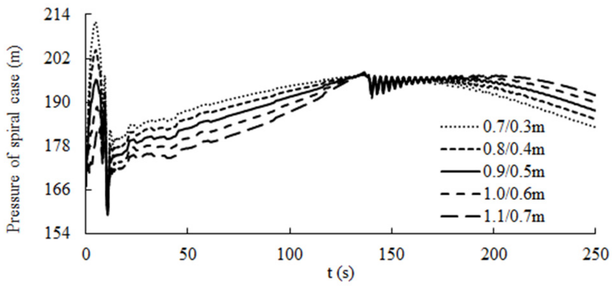

Figure 3. Pressure of spiral case with different PRV diameters (small unit)

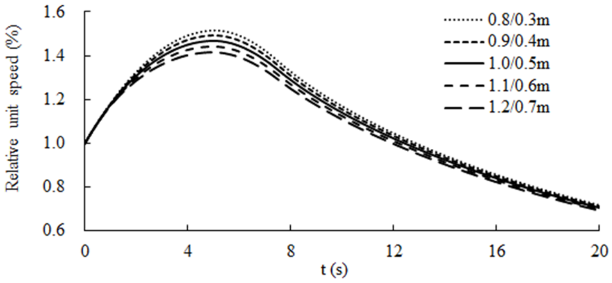

Figure 4. Relative unit speed with different PRV diameters (small unit)

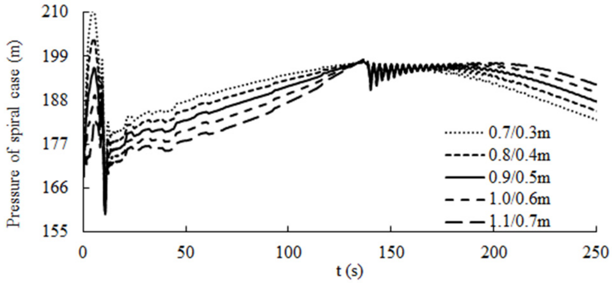

Figure 5. Pressure of spiral case with different PRV diameters (big unit)

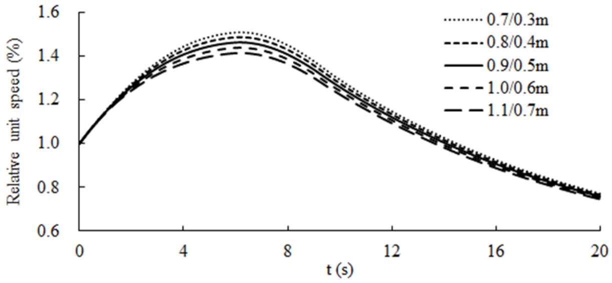

Figure 6. Relative unit speed with different PRV diameters (big unit)

It can be known that: comparing with only ST, the function of both ST and PRV can greatly reduce the $H_{max,s}$ and $N_{max,u}$. With the increase of PRV diameter, the maximum PRV flow increases greatly, the $N_{max,u}$ decreases greatly, and the $H_{max,s}$ decreases greatly at first and then increases slightly. When the diameter of PRV is 0.9/0.5m, the $H_{max,s}$ reaches its minimum value of 197.77/197.70m, and the $N_{max,u}$ is 46.71/46.79%, which all meet the regulating guarantee requirements and the safety margin is enough.

In order to further analyze the influence of PRV diameter on the $H_{max,s}$, with the small turbine as an example, the extremum pressure in the first and second wave as well as its corresponding ST water level are listed in Table 4.

Table 3. Results of large fluctuation transient process with different PRV diameter.

PRV diameter (m)	$H_{max,s}$ (m)	$N_{max,u}$ (%)	Maximum PRV flow (m^3/s)
0.7/0.3	210.97/212.06	51.44/51.52	15.85/3.20
0.8/0.4	203.56/204.31	49.16/49.26	19.70/5.52
0.9/0.5	197.77/197.70	46.71/46.79	23.51/8.22
1.0/0.6	197.98/197.93	44.18/44.19	27.05/11.04
1.1/0.7	198.28/198.23	41.70/41.55	30.18/13.69

It can be known that: comparing with only ST, the function of both ST and PRV can greatly reduce the $H_{max,s}$ and $N_{max,u}$. With the increase of PRV diameter, the maximum PRV flow increases greatly, the $N_{max,u}$ decreases greatly, and the $H_{max,s}$ decreases greatly at first and then increases slightly. When the diameter of PRV is 0.9/0.5m, the $H_{max,s}$ reaches its minimum value of 197.77/197.70m, and the $N_{max,u}$ is 46.71/46.79%, which all meet the regulating guarantee requirements and the safety margin is enough.

In order to further analyze the influence of PRV diameter on the $H_{max,s}$, with the small turbine as an example, the extremum pressure in the first and second wave as well as its corresponding ST water level are listed in Table 4.

Table 3. Detailed datas of spiral case pressure and ST water level.

PRV diameter (m)	The first wave of pressure rise			The second wave of pressure rise		
	Time (s)	Extremum (m)	ST water level (m)	Time (s)	Extremum (m)	ST water level (m)
0.7/0.3	4.79	212.06	1339.93	136.61	197.44	1360.77
0.8/0.4	4.79	204.31	1339.88	135.61	197.56	1359.79
0.9/0.5	4.86	196.20	1339.83	135.61	197.70	1358.51

1.0/0.6	5.48	188.81	1339.81	135.61	197.93	1356.99
1.1/0.7	6.37	183.31	1339.91	135.61	198.23	1355.26

It can be known that: The $H_{\max,s}$ in the first wave decrease greatly with the increase of PRV diameter. The time to reach extreme value become later but all before the full closure of guide vane. The ST water level is almost the same, which is because the closing time of guide vanes is so short that only a small quantity of water flows into ST when the pressure reaches its extreme value. The above analysis proves that the $H_{\max,s}$ in the first wave is controlled by the water hammer.

The $H_{\max,s}$ in the second wave increase slightly with the increase of PRV diameter. The time to reach extreme value is the same to the time of PRV fully closes. The water ST level at the time that the pressure reaches its extreme value decrease greatly, which is because the increase of PRV flow causes the decrease of the water flowing into ST. The above analysis proves that the $H_{\max,s}$ in the second wave is controlled by both water hammer and hydrostatic pressure. The hydrostatic pressure has slighter influence than water hammer in this station, so the $H_{\max,s}$ in the second wave increase very slightly with the increase of PRV diameter.

4.4 Hydraulic disturbance transient process

The layout of one tunnel with three units is adopted in the water conveyance system of this hydropower station, so there must be hydraulic disturbance among units. Therefore, the influence of PRV diameter on hydraulic disturbance should be analyzed. The control condition of hydraulic disturbance is as follows: the upstream water level is the maximum water level (1347.77m), the downstream water level is the design water level (1172.33m), the units work at the 1.1 times rated output, and the two big turbines reject load simultaneously while the small turbine works normally. The results of the calculation are shown in Figure 7 and Table 5.

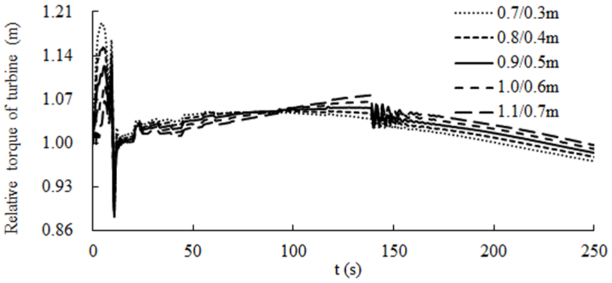

Figure 6. Relative unit speed with different PRV diameters (big unit)

Table 5. Calculation results of hydraulic disturbance with different PRV diameters.

PRV diameter (m)	$H_{\max,s}$ (m)	$T_{\max,u}$ (%)	$T_{\min,u}$ (%)
0.7/0.3	194.11	19.12	11.67
0.8/0.4	190.03	15.51	11.77
0.9/0.5	189.96	12.42	11.52
1.0/0.6	189.89	11.10	10.83
1.1/0.7	190.09	10.33	9.78

It can be shown that: the PRV diameter has a great influence on the $T_{\max,u}$ while has little influence on $T_{\min,u}$. With the increase of PRV diameter, the $T_{\max,u}$ increase greatly, which is because the increase of PRV diameter leads to the increase of the water flow through it and then the decrease of hydraulic disturbance. Besides, the closure of PRV can lead to a new wave of torque, but the variation is small, so $T_{\max,u}$ should be controlled by the disturbance caused by guide vanes closing. In order to reduce hydraulic disturbance, the maximum PRV flow should be approximate to the rated unit flow. When the PRV diameter is 0.9/0.5, the maximum increasing and decreasing rate of unit torque are 12.42% and 11.52% respectively, which are all within the allowance range.

From the analysis of large fluctuation and hydraulic disturbance transient process, the PRV diameter of 0.9/0.5m should be adopted for regulation in this station.

5 Conclusions

Based on the results of theoretical analysis and numerical calculation, the influence of PRV diameter on the transition process can be seen: during large fluctuation transient process, as the PRV diameter increases, the $N_{\max,u}$ decreases, and the $H_{\max,s}$ in the first wave decreases, but that in the second wave increases; During hydraulic disturbance transient process, the more approximate the maximum PRV flow to the rated unit flow, the smaller the $T_{\max,u}$. Thus three principles for selecting the diameter of PRV are concluded as follows:

(1) Making sure the $N_{\max,u}$ meet the guaranteed calculation requirements when guide vanes fast close;

(2) Under the condition of meeting the regulating guarantee requirements, the $H_{\max,s}$ of two waves should be approximate to each other by controlling the superposition of surge wave and water hammer;

(3) In order to alleviate the hydraulic disturbance among units, the maximum flow of the chosen PRV should be as close to the rated unit flow as possible.

The study provides references for the diameter selection of PRV in the diversion-type hydropower station with both ST and PRV.

Notation

The following symbols are used in this paper:
ST = surge tank
PRV=pressure regulating valve
$H_{\mathrm{max,s}}$ = maximum pressure of spiral case
$N_{\mathrm{max,u}}$ = maximum rising rate of unit speed
$T_{\mathrm{max,u}}$ = maximum rising rate of unit torque
$T_{\mathrm{min,u}}$ = maximum rising rate of unit torque

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