Analysis on influence of guide vanes closure laws of pump-turbine on load rejection transient process

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Abstract. In load rejection transient process, the sudden shut down of guide vanes may cause units speed rise and a sharp increase in water hammer pressure of diversion system, which endangers the safety operation of the power plant. Adopting reasonable guide vane closure law is a kind of economic and effective measurement to reduce the water hammer pressure and limit rotational speed increases. In this paper, combined with Guangzhou Pumped Storage Power Station plant A, the load rejection condition under different guide vanes closure laws is calculated and the key factor of guide vanes closure laws on the impact of the load rejection transition process is analyzed. The different inflection points, which are the closure modes, on the impact of unit speed change, water level fluctuation of surge tank, and the pressure fluctuation of volute inlet and draft tube inlet are further discussed. By compared with the calculation results, a reasonable guide vanes inflection point position can be determined according to security requirements and a reasonable guide vanes closure law can be attained to effectively coordinate the unit speed rise and the rapid pressure change in the load rejection transient process.

1. Introduction
In operation of pumped-storage power station, power grid system failure can lead to sudden load rejection of units, which causes units speed rise and a sharp increase in water hammer pressure of diversion system due to the sudden shut down of guide vanes [1]. It may severely endanger the safety operation of the power plant and shorten the service life of the units. Comparing with the solutions such as increasing units moment of inertia and setting up surge tank, adopting reasonable guide vane closure law is a kind of economic and effective measurement without extra investment, which can reduce the water hammer pressure and limit rotational speed increases [2].

At present the guide vanes closure laws for pumped storage power station are mainly the linear closure law and the multi-line closure law [3]. Linear closure law is that guide vanes will be closed at the same rate after load rejection. The optimization for linear closure law is simple and convenient, but the optimization law sometimes fails to control water hammer appreciation and speed rise in a reasonable range. Laws of multi-line mostly adopt two stage closure regulation: "first slow, then fast" and "first fast, then slow". Law of "first slow, and then fast" refers to the guide vanes shut down with smaller slope in the closing start section, then close with bigger slope quickly after the guide vanes...
opening reaching preset inflection point. Law of "first fast, then slow" refers to the guide vanes shut down with bigger slope in the closing start section, and then closes with smaller slope after the guide vane opening reaching the preset inflection point. And this kind of closure law is adopted by most conventional hydropower stations. Aimed at "S" characteristic features of pumped storage turbine in transient process, some scholars proposed delayed linear closure law [4][5], three stages line closure law [3], etc. Delayed linear closure law refers to the guide vanes not close immediately in load rejection condition and stays over a period of time with the guide vanes opening unchanged, then shut down with a given slope of straight line. Three stages closure law refers to the guide vane shut down quickly in the closing start section, and set a short pause when the operating point is near the region of "reversed S", and then quickly close the guide vanes. However, due to the huge inertia of governor hydraulic system, it is difficult to reach the required delay time. And there is little engineering application for these kinds of closure laws.

In this paper, the guide vanes closure laws of pumped-storage power station were reviewed. Combined with practical conditions of Guangzhou Pumped Storage Power Station plant A, the load rejection condition under different guide vanes closure laws was calculated and the results were processed and analyzed.

2. The main calculation parameters of Guangzhou Pumped Storage Power Station

Guangzhou Pumped Storage Power Station consists of reservoirs, water diversion system, surge chamber, pressure pipes and the underground powerhouse system. There are 4 units installed at plant A with a total capacity of 1200 thousand kW. Main parameters of the units are shown in table 1 and the diagram of Guangzhou Pumped Storage Power Station is shown in figure 1.

![Figure1. Guangzhou Pumped Storage Power Station.](image_url)

**Table 1. Main parameters of the unit.**

| Runner diameter | Rated speed | Rated flow | Moment of inertia | Rated output |
|-----------------|-------------|------------|-------------------|--------------|
| 3.866m          | 500rpm      | 62.88m³/s  | 3600tm²        | 306MW       |

3. Computational analysis

According to the previous given hydrological data, the method of characteristics[6] is used and the relevant mathematical models and water hammer equations of the Guangzhou Pumped Storage Power Station are established. The load rejection transient process with the unit head of 506m is calculated using the simulation software. The results of different guide vanes closure laws are analyzed.

The table 2 and the figure 2 both show five different kinds of guide vanes closure laws. The total closing time and the inflection point time under five conditions are constant, while the inflection point ranges from 0.63 to 0.30. The guide vanes closure mode under GK1 and GK2 is “first slow, then fast” and the GK3 is a linear closure mode, and the guide vanes closure mode under GK4 and GK5 is “first
fast, then slow”. The table 3 shows the unit speed result of load rejection using five different kinds of guide vanes closure laws.

| Condition | Inflection point time(s) | Inflection point | Total closing time(s) |
|-----------|--------------------------|------------------|-----------------------|
| GK1       | 20.4                     | 0.63             | 43.5                  |
| GK2       | 20.4                     | 0.60             | 43.5                  |
| GK3       | 20.4                     | 0.57             | 43.5                  |
| GK4       | 20.4                     | 0.40             | 43.5                  |
| GK5       | 20.4                     | 0.30             | 43.5                  |

The rise rate of the unit speed appears at different time under five different kinds of guide vanes closure laws. An obvious regulation can be observed with figure 3. The maximum rise rate firstly appears under GK5 and the value of the rise rate is maximum among the five conditions, while the minimum value of the rise rate appears at GK1. When total closing time and the inflection point time are constant, the maximum of speed rise rate increases with the inflection point ranged from 0.63 to 0.3. It can be obtained that the closure mode “first fast, then slow” make the unit speed change greatly, and there is the maximum rise rate of speed. By contrast, the closure mode “first slow, then fast” makes the speed changeless violently.

The water level fluctuation of upper surge chamber and tail water surge chamber under five different kinds of guide vanes closure laws are shown in figure 4 (a) and (b) respectively. When total closing time and the inflection point time are constant, the water level fluctuation cycle increases with the inflection point ranged from 0.3 to 0.63. It can be obtained that the closure mode “first slow, then fast” make the water level fluctuate greatly with a maximum water level rise. By contrast, the closure mode “first fast, then slow” make the water level fluctuate gently.
With five different kinds of guide vanes closure laws adopted, there is large pressure fluctuation at the volute inlet and the draft tube inlet, and the pressure fluctuation cycles of volute inlet and draft tube inlet are affected by water level fluctuation of upstream and downstream surge chamber respectively, as shown in figure 5 (a) and figure 6 (a). The maximum of pressure rise at the volute inlet during the guide vanes closure process appears under GK5, while the minimum rise value appears at GK1, shown in figure 5(a). When total closing time and the inflection point time are constant, the maximum of rise pressure at the volute inlet increases with the inflection point ranged from 0.63 to 0.3. However, there is more complex pressure fluctuation at the draft tube inlet, as can be seen from figure 6(a) and (b), the pressure changes more quickly but has no general regularity.

Figure 4. Water level fluctuation of surge chamber under five kinds of guide vanes closure laws.

Figure 5. Pressure fluctuation of volute inlet under five different kinds of guide vanes closure laws.
4. The conclusion
In this paper, combined with the practical situation of Guangzhou Pumped Storage Power Station, the key factor of guide vanes closure laws is analyzed on the impact of the load rejection transition process of pump-turbine units. The different inflection points on the impact of unit change, water level fluctuation of surge tank, and the pressure fluctuation of volute inlet and draft tube inlet are further discussed respectively. When the inflection point ranges from 0.63 to 0.30, which is the guide vanes closure mode change from “first slow, then fast”, the linear closure mode, to “first fast, then slow”, the conclusions are as follows:

1) The maximum of speed rise rate increases gradually.
2) The water level of upper surge chamber and tail water surge chamber fluctuates more gently, and water level fluctuation cycle decreases gradually.
3) The pressure rise at the volute inlet increase gradually during the guide vanes closure process, while the pressure changes no general regularity at the draft tube inlet.

By compared with the calculation results and according to security requirements, the guide vanes closure law of GK1 can be determined and attend to effectively coordinate the unit speed rise and the rapid pressure change in the load rejection transient process.

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