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Hydro turbine governor's power control of hydroelectric unit with sloping ceiling tailrace tunnel

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Abstract. The primary frequency regulation and load regulation transient process when the hydro turbine governor is under the power mode of hydropower unit with sloping ceiling tailrace are analysed by field test and numerical simulation in this paper. A simulation method based on "three-zone model" to simulate small fluctuation transient process of the sloping ceiling tailrace is proposed. The simulation model of hydraulic turbine governor power mode is established by governor's PLC program identification and parameter measurement, and the simulation model is verified by the test. The slow-fast-slow "three-stage regulation" method which can improve the dynamic quality of hydro turbine governor power mode is proposed. The power regulation strategy and parameters are optimized by numerical simulation, the performance of primary frequency regulation and load regulation transient process when the hydro turbine governor is under power mode are improved significantly.

1. Introduction

Hydroelectric units undertake the tasks of peak load and frequency regulation in the grid. The regulation performance has affected the stability of power system and the coordination between units and grid. There are three regulation modes of hydro turbine governor at present: frequency regulation mode, opening regulation mode and power regulation mode [1]. Power regulation mode is a kind of mode which is adopted when the hydroelectric unit is under the grid interconnection operation. When the governor is under the power mode, the monitoring system sends the power given value to the governor, and the power closed loop regulation is completed by the governor, which has the advantages of good regulating performance and achieving the coordinated control of primary frequency modulation and AGC.so the power regulation mode has been widely applied in the large hydropower stations.

For the hydroelectric units with sloping ceiling tailrace [2], the regulation quality when the governor is under the power mode is greatly influenced by the complex hydraulic characteristics in sloping ceiling tailrace and nonlinear properties of the hydro turbine. Once the governor control strategy and parameter selection are improper, it may cause the power sharp anti-regulation and cycle fluctuation, which has great impact on the safe and economical operation of the hydropower station and the stability of the grid.

The studies on hydro turbine governor's power regulation are mainly concentrated on modes. The direct and indirect power regulation structures and there implementation methods are analyzed in [1]. In [3] ,the adjusting speed and accuracy of the monitoring system's pulse power regulation mode and the governor's power closed loop regulation mode are compared by field test. The researches on the hydraulic transient process of sloping ceiling tailrace are mainly concentrated on the profile design [4], steady flow analysis [5], numerical simulation of unsteady flow [6], stability analysis [7,8] etc.

Numerical simulation combined with field measurement is used in this paper to have a deeply study on the governor's power mode transient process of hydroelectric unit with sloping ceiling tailrace. Hydraulic characteristics of sloping ceiling tailrace tunnel are simulated by using "three - zone model" and the simulation model of hydraulic turbine governor is established by using model identification and parameter measurement method, and the simulation model is validated by site prototype test results. The control strategy and control parameters of governor are optimized based on field test and numerical simulation, which effectively improve the primary frequency regulation and dynamic quality of AGC load adjustment transient process when the hydro turbine governor is under the power model.

2. Numerical simulation model

Hydro turbine regulating system consists of three subsystems which are intercoupling: water diversion system, hydro turbine system, governor system.

2.1. Simulation model of sloping ceiling tailrace tunnel

The whole tail tunnel with sloping ceiling can be divided into pressure flow area, free-surface-pressure flow area and open channel flow area according to the difference of hydraulic characteristics, it is shown in Figure 1.

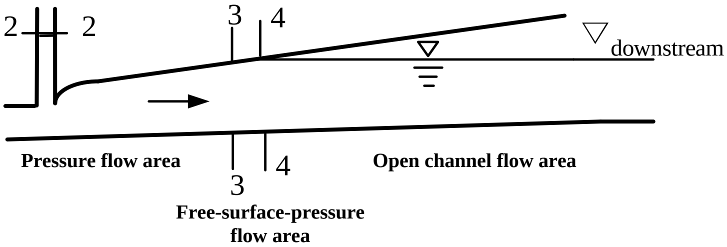

Figure 1. Three-zone model schematic diagram of sloping ceiling tailrace tunnel.

2.1.1. Model of pressure flow area For pressure flow area, it's simulated by using equations of rigid water hammer[9].

2.1.2. Model of free-surface-pressure flow area For free-surface-pressure flow area, the simulation model can be obtained according to the continuity equation.

$$q_3 - q_4 = \frac{c_4}{2}\frac{L_{4x}}{Q_r}\sin(2\theta)\frac{B_4}{n} \tag{1}$$

$$h_3 - h_4 = \frac{L_{4x}Q_r}{H_r g A_4}\frac{d(q_3 - q_4)}{dt} \tag{2}$$

$$h_4 = \frac{L_{4x}\sin\theta}{H_r} \tag{3}$$

Where H_{40} is the pressure of section 4 before disturbance, H_4 is the pressure of section 4 after disturbance, Q_{40} is the discharge of section 4 before disturbance, Q_4 is the discharge of section 4 after disturbance, $h_4 = \frac{H_4 - H_{40}}{H_r} = \frac{\Delta H_4}{H_r}$, $q_4 = \frac{Q_4 - Q_{40}}{Q_r} = \frac{\Delta Q_4}{Q_r}$; L_{4x} which is unknown is the channel length of free-surface-pressure flow area. A_4 is the flow area of section 4. θ is the slope of upper ceiling of sloping ceiling tailrace tunnel. g is acceleration of gravity. B_4 is the width of section 4. n is section coefficient of tailrace tunnel, for rectangular tailrace, $n = 2$, for city-gate section channel, $n = 3$.

2.1.3. Model of open channel flow area According to Saint-Venant equations and ignoring the nonlinear terms , the below transform can be get.

$$\frac{h_4(s)}{q_4(s)} = h_{w5}\frac{T_{r5}s + 2f_5}{\frac{1}{8}T_{r5}^2 s^2 + \frac{1}{2}T_{r5}f_5 + 1 + \frac{f_5^2}{2}} \tag{4}$$

Where $h_{w5} = c_5 Q_r / 2gA_5 H_r$, $f_5 = \lambda_5 Q_r L_5 / 8R_5 A_5 c_5$. λ_5 is the friction factor of head loss of free surface flow area. R_5 is hydraulic radius of free surface flow area. $T_{r5} = \frac{2L_5}{c_5}$, L_5 is the length of free surface flow area. $c_5 = \sqrt{gH_{5m}}$ is wave velocity of free surface flow area. A_5 is the flow area of free surface flow area. H_{5m} is the initial water depth of free surface flow area.

2.1.4. Simulation model of sloping ceiling tailrace tunnel According to the mathematical model of pressure flow area, free-surface-pressure flow area and free surface flow area. Equations of simulation model of sloping ceiling tailrace tunnel can be get as shown in (5). This is the system of ordinary differential equations which is easily to be solved.

$$\begin{cases} \frac{L_3 Q_r}{H_r g A_3}\frac{dq_3}{dt} = h_2 - h_3 - \frac{2h_{f3}q_3 Q_r}{H_r Q_{30}} \\ q_3 - q_4 = \frac{c_4}{2}\frac{L_{4x}}{Q_r}\sin(2\theta)\frac{B_4}{n} \\ \frac{L_{4x}Q_r}{H_r g A_4}\frac{d(q_3 - q_4)}{dt} = h_3 - h_4 \\ h_4 = \frac{L_{4x}\sin\theta}{H_r} \\ \frac{h_4(s)}{q_4(s)} = h_{w5}\frac{T_{r5}s + 2f_5}{\frac{1}{8}T_{r5}^2 s^2 + \frac{1}{2}T_{r5}f_5 + 1 + \frac{f_5^2}{2}} \end{cases} \tag{5}$$

2.2. Simulation model of hydraulic turbine governor

Hydraulic turbine governor includes regulator and servo-system.

For the governor's power control, governor manufacturers have different ways to achieve at present, and there is no unified standard. So it is difficult to simulate the governor's power mode. The simulation model only can be established based on PLC or PCC control program as shown in Figure 2. In case of one hydroelectric power station, the PLC of hydraulic turbine governor is Schneider premium, and the programming platform is PL7 Pro.

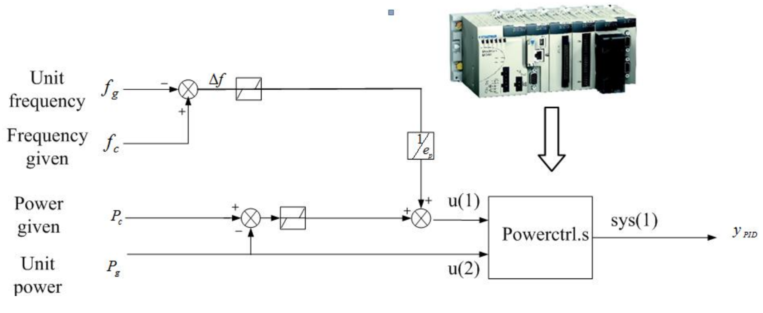

Figure 2. Regulator model of hydraulic turbine governor power mode.

The actuator of hydraulic turbine governor is generally composed of hydraulic servo-system, which includes electro-hydraulic converter, main distributing valve and guide vane servomotor. Field measurement and parameter identification are used to model the hydraulic servo-system accurately. In document [10], there have definite requirements for the parameter identification of hydraulic turbine governor.

2.3. Model of hydraulic turbine

To simulate the nonlinear properties of hydraulic turbine accurately, the nonlinear model based on model hydroturbine comprehensive characteristic curve is adopted in simulation. The model hydroturbine comprehensive characteristic curve is converted to hydroturbine discharge characteristic curve and torque characteristic curve, and the interpolation calculation is used.

3. Comparison between simulation and test

In load regulation transition process of a hydropower unit with sloping ceiling tailrace tunnel, the simulation and test results of power, guide vane servomotor stock and outlet pressure of draft tube are compared as shown in Figure 3~8 In the figures, y is the guide vane opening, P is the unit active power ,Hs is the draft tube outlet pressure.

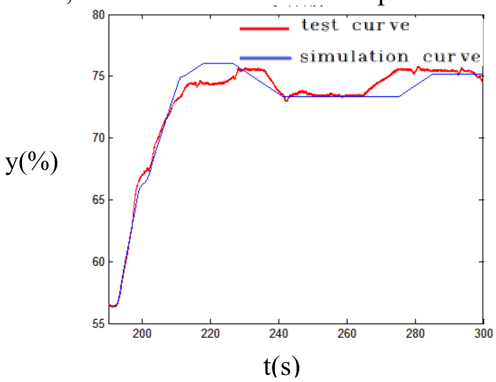

Figure 3. Comparison between simulation and test of guide vane opening in load increasing transient process.

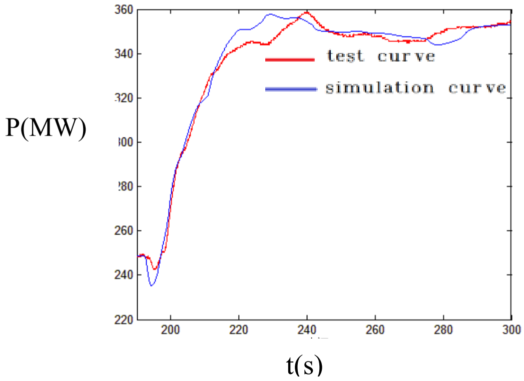

Figure 4. Comparison between simulation and test of active power in load increasing transient process.

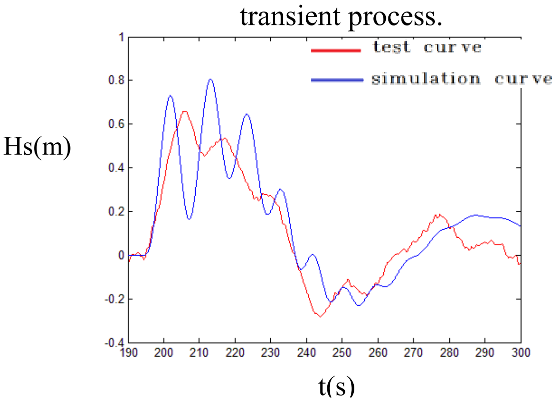

Figure 5. Comparison between simulation and test of draft tube outlet **pressure** in load increasing transient process.

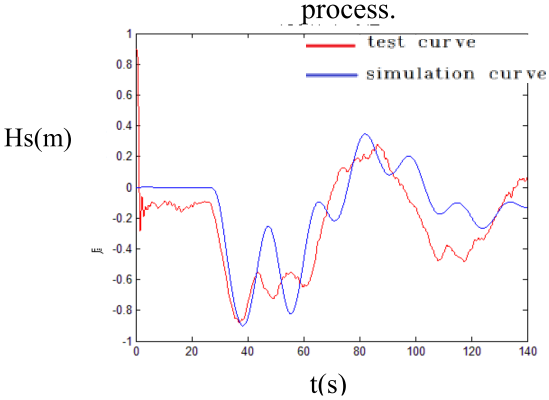

Figure 6. Comparison between simulation and test of draft tube **outlet** pressure in load shedding transient process.

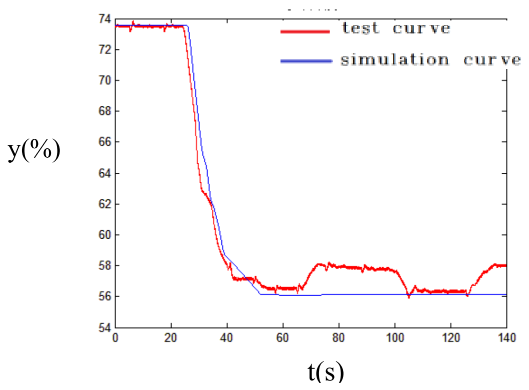

Figure 7. Comparison between simulation and test of guide vane opening in load shedding transient process.

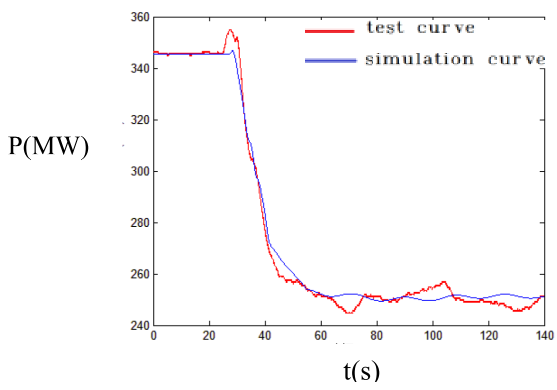

Figure 8. Comparison between simulation and test of active power in load shedding transient process.

The field tests indicated that: hydraulic characteristics of sloping ceiling tailrace tunnel have great impacts on the hydro turbine regulating system. 1)The great power anti-regulation is caused and it affects the power governing speed and causes the lag time of primary frequency regulation longer, which slows the AGC governing speed and cannot meet the requirements of the grid. 2)After the load regulation and primary frequency regulation, low-frequency pressure oscillation is appeared in the outlet of draft tube, which degrades the regulating quality and precision.

The comparison between simulation and test shows that: simulation results of increasing and shedding load transient process when the governor is under the power mode basically coincide with the tests; simulation results of draft tube outlet pressure coincide with the tests, which proves that the simulation model of sloping ceiling tailrace tunnel used in this paper is accurate.

4. Optimization of control strategy and parameters based on simulation

Hydraulic turbine has complex nonlinear and parameter-time-varying properties. It is difficult to reflect the response characteristics of hydropower unit comprehensively by single field test, so power regulation performance must be analyzed comprehensively by combining field test with simulation, and the control strategy and parameters of hydraulic turbine governor can be optimized to ensure good dynamic regulating performance of the entire governing system.

To make sure the stability of governing system and meet the regulation speed requirements of grid, the power anti-regulation must be reduced and the speed of power regulation must be increased and the stability must be ensured. So the slow-fast-slow "three-stage regulation" method is proposed, it can improve the dynamic quality of hydro turbine governing system when the governor is under power mode. Slow-fast-slow three-stage speed regulation is shown in Figure 9.

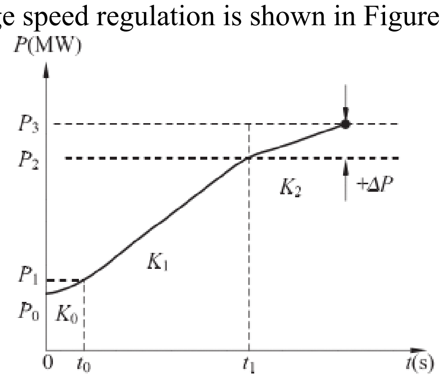

Figure 9. Three-stage model regulation schematic diagram.

The direct power regulation described in [1] is adopted in a hydropower turbine governor with sloping ceiling tailrace tunnel. The field test indicated that: the anti-regulation of power regulation was large and there had obvious overshoot phenomenon when the governor is under power mode, which had caused that the primary frequency regulation and dynamic quality of AGC load adjustment process couldn't meet the grid's requirements [2]. So the power control strategy was changed into slow-fast-slow three-stage regulation shown in Figure.9 and governor parameters under various conditions were optimized by the simulation to improve the regulation performance. The results of optimization are shown in Table 1.

Table 1. The results of optimization.

conditions	Optimal parameter
primary frequency regulation	K0=0.1 K1=0.3 K2=0.01 t0=1.05 ΔP=±8MW
load regulation	K0=0.4 K1=1.6 K2=0.13 t0=3.5 ΔP=±31MW

Primary frequency regulation and load regulation transient process of hydropower unit with sloping ceiling tailrace tunnel before and after optimization were analyzed by numerical simulation. The change process of guide vane opening and power is shown in Figure10, 11. In the figures, y is the guide vane opening, P is the unit active power.

The comparisons of simulation results show that: After the optimization of governor control strategy and parameters, the load regulation transient process performance is improved significantly and the power response speed of the unit increases obviously, power anti-regulation value is reduced. Power overshoot phenomenon almost disappeared. In the regulation process, guide vane opening and power changes stably, and there is no periodic oscillation, the power performance of units has met the AGC requirements of the grid.

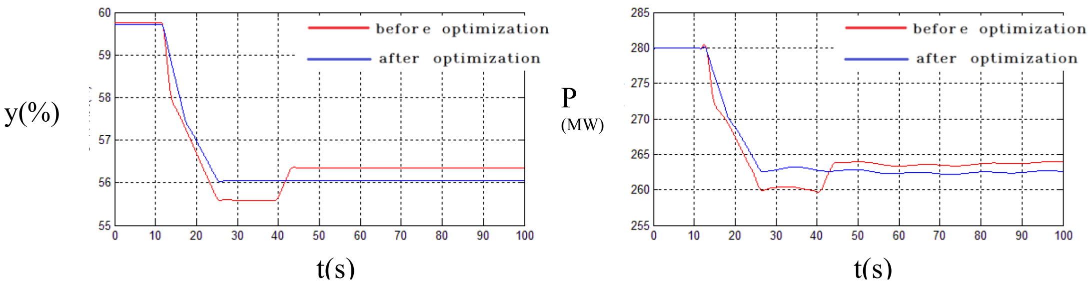

Figure 10. Comparison of simulation results of load regulation before and after optimization01.

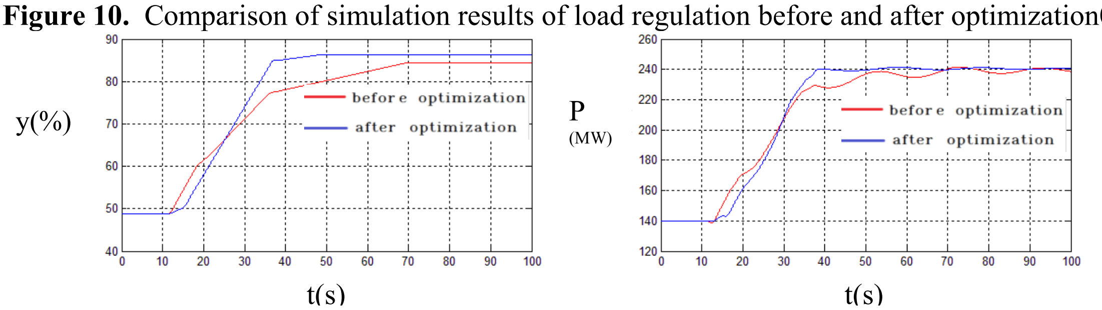

Figure 11. Comparison of simulation results of load regulation before and after optimization02.

5. Conclusions

According to the hydraulic characteristic and the characteristic of small fluctuation transient process in sloping ceiling tailrace tunnel, a method based on "three-zone model" to simulate small fluctuation transient process of sloping ceiling tailrace tunnel is proposed. The simulation model of hydraulic turbine governor power mode is established by governor’s PLC program identification and field measurement. The comparison between simulation and test shows that simulation results coincide with the results of test, which proves that the simulation model of sloping ceiling tailrace tunnel used in this paper is accurate. The slow-fast-slow "three-stage regulation" method which can improve the dynamic quality of hydro turbine governor’s power regulation is proposed. Active power response speed of unit is faster and power anti-regulation value is decreased by optimization of governor control strategy and parameters, and the performance of primary frequency regulation and load regulation transient process under the hydro turbine governor’s power mode is improved significantly.

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