Parameters design and simulation research of water pressure phase compensation link in governor side of hydro turbine generating unit

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Abstract: Using the phase signal of water pressure oscillation in inlet of turbine as auxiliary signal of governor can restrain the water pressure oscillation of pipe. Refer to the structure of power system stabilizer, two structure types of leading phase compensation link are given in this paper, and its structure design and parameters assignment are analyzed. Based on the operation simulation system of the hydro turbine generating sets, simulation research is carried out from two aspects, (i) effect of two structure types phase compensation link on inhibitory effect of water pressure; (ii) effect of the amplitude gain of compensation branch on the compensation control. Research shows that the leading phase compensation link proposed can effectively reduce the water pressure oscillation for transient process with high water pressure fluctuation, but its effect on normal active power regulation is very little.

1. Introductions
The hydro turbine generating units (HTGS) is a complex multi-field coupling system with hydraulic-mechanical-electric, its dynamic characteristics research of the internal correlations have obtained many beneficial progresses [1]. The research of internal dynamics characteristics also needs to realize its control idea by the controller design at last. Therefore, from the perspective of controller design to research the measures to improve the operation stability of the HTGS is the most direct technical means, for example, the hydraulic system, the hydro turbine, the generator and controller are integrated into a unified framework to simulate and calculate [2-4], etc.

The effect of the hydraulic dynamic changes of the water diversion system on the hydro turbine is produced by the changes of water head and flow in the inlet section of the turbine [5-7]. Therefore, water pressure fluctuation is the most direct factor affecting the operation stability of the HTGS. However, from the perspective of the structure of hydraulic system and its dynamic characteristics to research the technology and methods of restraining water pressure fluctuation, the research progress is relatively slow. The surge tank technology is the most typical technology in the kinds of method [8], in which the systemic research has been done from the structure type, structure parameters, and its impact on large and small fluctuations. The water pressure fluctuation is caused by the guide vane.
fluctuation. Therefore, it is the most natural idea to connect hydraulic dynamics with governor control. About introducing the water pressure signals into control design of governor of the hydro turbine, the reference [9] mentions that some of special researches had been done, but the literature available is limited. The PI and PID control algorithms using the water pressure feedback signal have played a certain role in restraining the water pressure fluctuation [10,11]. In essence, this kind of water pressure feedback is based on the amplitude of water pressure.

Refer to the design idea of the Power System Stabilizer (PSS), a new method is proposed to restrain the water pressure fluctuation in [12], it is called as the Hydraulic Oscillation Stabilizer (HOS). The relation between the guide vane fluctuation and the water pressure oscillation is further researched [13], in which the phase of the water pressure oscillation and the guide vane fluctuation is opposite, their phase difference is the 180°. The characteristic provides the more direct design consideration for the phase compensation of the water pressure.

Based on the phase characteristics of water pressure and guide vane fluctuation, and referring the structure type of the classical PSS, this paper presents a method of realization of water pressure phase compensation, and conducts parameter design and simulation research.

2. Structure of compensation link

The phase of water pressure fluctuation in inlet of hydro turbine is opposite to the phase of the guide vane fluctuation [13]. From view of dynamics, this phenomenon can be considered as the serve system, which motion of the hydraulic system is a forced oscillation, and its period changes with the period of the guide vane fluctuation. On the other hand, the motion of guide vane is approximately linear with motion of the main servomotor. Therefore, the phase signal of the water pressure fluctuation can be extracted from the displacement of the main servomotor. In this way, the difficulty of extracting signal and time delay of measuring link are avoid.

The torque of hydro turbine is affected by the head and flow in the inlet of hydro turbine, so direct result of the water pressure fluctuation is the power oscillation of hydro turbine. The power oscillation of hydro turbine is similar to the low frequency oscillation of power system in form. Therefore, the signal structure mode of the PSS can be employed to construct the additional control signal of the water pressure compensation link. The output of the compensation unit and the output of the PID controller are summed to form new control signals. The parallel PID structure of governor with water pressure phase compensation is shown in figure 1.

![Figure 1. Control structure of the water pressure phase compensation.](image-url)
In figure 1, the water pressure compensation unit is constructed in the form of traditional PSS. Two compensation branches are given in two ways, and only one of them needs to be selected in the application. There are two links of leading phase in the branch 2, which can provide more leading phase.

The $\Delta p$ is the power error of given power and measured power in relative value; the $\Delta f$ is the frequency error of given frequency and measured frequency in relative value; the $b_p$ is the adjustable rate, $K_p$, $K_D$ and $K_I$ are the proportion, differential and integration constant of the parallel PID controller respectively; the $T_{in}$ is the time constant of the actual differential element in (s); the $T_p$ is the time constant of the main servomotor in (s); the $\Delta y$ is the increment of the main servomotor displacement in relative value, it is taken as the phase compensation signal of water pressure; the $K_h$ is the gain coefficient; the $T_{h1}$ is the time constant of the filter element; the $T_{h2}$ and $K_{h2}$ are the time constant and gain coefficient of the lead phase compensation link respectively; the $T_{h22}$ and $T_{h23}$ are the time constant of the second lead phase compensation in (s) respectively.

3. Parameters design

The filter element in the water pressure compensation branch is used to filter the high frequency noise wave generated in measurement process of the main servomotor displacement feedback. Assumption the angular frequency of the main servomotor fluctuation is $\omega_g$. Then substitute the $j\omega_g$ into the transfer function of filter element:

$$\frac{T_{h1}s}{1+T_{h1}s} = \frac{T_{h1}^2\omega_g^2 + jT_{h1}\omega_g}{1+T_{h1}^2\omega_g^2}$$

The amplitude is

$$A_1 = \frac{T_{h1}\omega_g\sqrt{(T_{h1}\omega_g)^2 + 1}}{1+T_{h1}^2\omega_g^2}$$

The phase angle is:

$$\theta_1 = a \tan \left( \frac{1}{T_{h1}\omega_g} \right)$$

If selected parameters satisfy the condition $T_{h1}\omega_g>>1$, then the gain of filter element is close to 1, and its phase angle is near to 0.

As such, assumption the angular frequency of the main servomotor fluctuation is $\omega_g$. Then substitute the $j\omega_g$ into the transfer function of the leading phase element. The amplitude gain is:

$$A_2 = \frac{K_{h2}\omega_g\sqrt{(T_{h2}\omega_g)^2 + 1}}{1+T_{h2}^2\omega_g^2}$$

The phase gain is:

$$\theta_2 = a \tan \left( \frac{1}{T_{h2}\omega_g} \right)$$

Obviously, the phase angle size is determined by the $T_{h2}\omega_g$. If selected parameters satisfy the condition $T_{h2}\omega_g<<1$, then its phase angle is near to 90°.

The amplitude gain of the second leading phase compensation element is:

$$A_3 = \sqrt{\left[1 + T_{h22}\omega_g\right]^2 + T_{h22}^2 - T_{h23}^2}\omega_g^2}$$

Its phase angle is:

$$\theta_3 = a \tan \left( \frac{T_{h23} - T_{h22}}{1 + T_{h22}T_{h23}\omega_g} \right)$$
If selected parameters satisfy the condition $T_{h23} > T_{h22}$, then the phase angle is the lead phase angle. There is no discussion on the relative size of the amplitude gain of the compensation signal and the amplitude of the PID output signal. If the gain of signal from the point $\Delta y$ to $y$ in the water pressure compensated branch signal is 1, amplitude of the water pressure compensation branch $\Delta u'$ is equivalent with amplitude of the traditional PID output. The so-called amplitude equivalent refers to the signal amplitude that the output end of the main servomotor gets the same output as the input signal amplitude. According to this condition, the gain coefficient of the compensation branch 1 is:

$$K_{bh} = \frac{1 + T_{h1}^2 \omega_g^2}{T_{h0} \omega_g \sqrt{(T_{h0} \omega_g)^2 + 1} K_{h2} \omega_g \sqrt{(T_{h2} \omega_g)^2 + 1} \sqrt{(T_{y} \omega_g)^2 + 1}}$$

(8)

And the gain coefficient of the compensation branch 2 is:

$$K_{bh1} = \frac{1 + T_{h0}^2 \omega_g^2}{T_{h0} \omega_g \sqrt{(T_{h0} \omega_g)^2 + 1} K_{h2} \omega_g \sqrt{(T_{h2} \omega_g)^2 + 1} \sqrt{[1 + T_{h22} T_{h23} \omega_g^2 + [T_{h22} - T_{h23}] \omega_g^2 \sqrt{(T_{y} \omega_g)^2 + 1}}$$

(9)

The angular frequency of the main servomotor fluctuation $\omega_g$ is a key parameter. The connection between the main servomotor and the guide vane is approximately rigid connection, so their fluctuation frequency is the same. From above expressions, the phase shift of the main servomotor position feedback can be realized so long as the phase angle compensation condition is satisfied. Therefore, the travel period of water hammer wave $2T_e$ is selected as the calculation basis, that is $\omega_g = 2\pi/2T_e$. The $T_e = L/\alpha$ is the travel time of the water hammer wave in diversion system pipeline, the $L$ is the length of pipeline, $\alpha$ is the travel speed of water hammer wave.

According the structure given by the figure 1, the discrete algorithm of filter element is:

$$\Delta v(k) = \frac{T_{k1}}{T + T_{k1}} [\Delta v(k-1) + K_h \Delta y(k) - K_h \Delta y(k-1)]$$

(10)

The discrete algorithm of the first lead phase compensation element is:

$$\Delta u'(k) = \frac{1}{T + T_{h2}} [T_{h2} \Delta u'(k-1) + K_{h2} \Delta v(k) - K_{h2} \Delta v(k-1)]$$

(11)

The discrete algorithm of the second lead phase compensation element is:

$$\Delta u''(k) = \frac{1}{T + T_{h22}} [T_{h22} \Delta u''(k-1) + (T + T_{h23}) \Delta u'(k) - T_{h23} \Delta u'(k-1)]$$

(12)

where the $T$ is the discrete time in (s), and is equal to the execution period of the PID controller.

4. Operation simulation system

In order to better simulate the operation condition of the HTGS, a single machine and single pipeline system is constructed.

Main parameters of the hydraulic system: the length of pipeline $L = 500$ (m), the diameter of pipeline $D = 3.5$ (m), rated flow $Q_r = 53.5$ (m$^3$ s$^{-1}$), rated head $H_r = 312$ (m), travel speed of water hammer wave $\alpha = 1100$ (m s$^{-1}$), the time constant of main servomotor $T_y = 0.5$ (s).

The parallel PID governor in figure 1: $K_p = 5.0$, $K_v = 2.5$, $K_i = 1.5$, and $b = 0.04$.

The excitation control system adopts the PID control of the terminal voltage: $K_{p1} = 10$, $K_{i1} = 5$, $K_{d1} = 0.001$.

The model of the hydraulic system and hydro turbine is the differential equation model with elastic water hammer.

The generator model is the third orders differential equation model with single machine and infinite bus system. The main parameters: the inertia time constant of generator $T_i = 8.999$ (s), the damping coefficient $D = 5$. 
Single-machine infinite bus system is shown in figure 2.

Figure 2. Single machine infinite bus system.

5. Simulation research

Initial equilibrium point is $p_e=0.9$ (pu) and $Q_e=0.3$ (pu).

It is assumed that a solid three-phase fault is occurred at point F at $t=1.0$ (s), and the fault is cleared by isolating the fault circuit at $t=1.1$ (s). Fault point is simulated with an equivalent reactance $X_L=2.0$ (pu). Obviously, system structure has been changed at fault before and after.

According to the characteristics data of hydraulic system, the travel time of water hammer wave is $T_e=0.4545$ (s). So the angular frequency is selected as $\omega_g=2\pi/(2T_e)=6.9115$ (rad s$^{-1}$).

Parameters of the lead phase compensation branch 1: $T_{h1}=10/\omega_g=1.4469$ (s), $T_{h2}=0.1/\omega_g =0.0145$ (s), $K_{h2}=0.1$, $K_h=5.2572$, $\theta_1=5.7106^\circ$, $\theta_2=84.2894^\circ$.

Parameters of the lead phase compensation branch 2: $T_{h1}=10/\omega_g=1.4469$ (s), $T_{h2}=0.1/\omega_g =0.0145$ (s), $K_{h2}=0.1$, $K_h=0.9151$, $T_{h2}=0.1$ (s), $T_{h22}=1.0$ (s), $\theta_1=5.7106^\circ$, $\theta_2=84.2894^\circ$, $\theta_3=47.1169^\circ$.

In figure 1, the main servomotor has the phase angle lag $\tan(\frac{-\gamma W_g}{T_e})$. Considering $\omega_g=2\pi/(2T_e)$, the lag phase is the $\tan(\frac{-\gamma W_g}{T_e})=-73.86^\circ$, which almost cancels out the leading phase angle generated by the compensation branch 1. This is the starting point of this paper to add a leading phase compensation element to provide more leading phase angle, which is the lead phase compensation branch 2.

In order to check the working state of the water pressure compensation branch, the output signal of the phase compensation branch $\Delta u'$ does not join into the PID output temporarily. Main output signal are given in figure 3.

The figure 3(a) is the phase changes of the branch 1, while the figure 3(b) is the phase changes of the branch 2. From figure 3, leading phase design achieves the expect purpose.

The amplitude of the water pressure compensation signal $\Delta u'$ or $\Delta u''$ is worth discussing. If the value of the $\Delta u'$ or $\Delta u''$ is much smaller than the output amplitude of the PID unit, then the water pressure compensation signal has little effect on the PID output, and the expected effect of water pressure compensation is lost. If the signal amplitude is too large, the PID signal is submerged by the water pressure compensation signal, and then control is changed into approximate pure hydraulic
feedback control. In order to explore the problem of the amplitude of the water pressure compensation signal, taken the branch 1 as case and given the different gain of branch 1, the simulation is conducted under the same working condition. The head of hydro turbine and output power of generator in transient are shown in figure 4.

Figure 4. Changes of the main parameters given different $K_h$.

The figure 4(a) is the head changes of hydro turbine, while the figure 4(b) is the power changes of the generator.

In figure 4, the solid line is the case under $K_h=0$, while the dotted line is the case under $K_h=1$, 3 and 5. Obviously, using the water pressure compensation, the fluctuation amplitude of hydro turbine head is obviously decreased, and the larger the $K_h$ is, the smaller the fluctuation amplitude of the hydro turbine head is. In figure 4(b), under fault disturbance, the active amplitude of generator is slightly increased. Overall, the water pressure fluctuation is smaller, the operation stability of the whole HTGS is improved.

The simulation result of water pressure compensation branch 2 is similar to that of compensation branch 1.

The normal power regulation of the HTGS, the active power from $p_e=0.6$ (pu) to $p_e=1.0$ (pu), the changes of the power and head are shown in figure 5.

Figure 5. Active power and head changes under normal power regulation.

The figure 5(a) is the power changes of the generator, while the figure 5(b) is the head changes of the hydro turbine.
In figure 5, the solid line is configured with phase compensation, while the dotted line is not configured phase compensation. The figure 5 shows that the hydro turbine head under two control conditions is near same, the water pressure phase compensation has no effect on normal power regulation.

6. Conclusions
The structure and parameters design of water pressure phase compensation are researched in this paper. It provides a new research way for the stability control of the HTGS. The following conclusions are given in this paper:

(i) According to the characteristic that the phase error between the guide vane fluctuation and the water pressure fluctuation is 180°, it is appropriate that selected the displacement signal of the main relays takes as the signal of water pressure fluctuation. Moreover, this method is simpler.

(ii) Two lead phase compensation models proposed in this paper can achieve the purpose of restraining the fluctuation of water pressure. The proposed parameters design method is simple and intuitive.

(iii) The water pressure phase compensation structure proposed in this paper is applicable to the transient condition with large fluctuation of water pressure, which has no effect on the normal regulation of the HTGS.

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