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Research of the Impact of the Regulator Parameters in Steam Turbine Speed Governor System on the Damping of the Grid

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Abstract: Established a mathematical model of a 600 MW steam turbine speed governor system based on practical data. The frequency domain analysis indicates that different regulator parameters of turbine governor have different influences on the damping characteristics of the power system. If the regulator parameters are improper, they can cause the low frequency oscillation of the Grid. Through the analysis of the mechanical damping torque coefficient under the various combinations of the regulator parameters, this paper gives the qualitative trends of the system damping when the control parameters change. Through the analysis of stability of the system, this paper gives the range of the proper regulator parameters. And bring forward a setting method of the steam turbine regulator parameters based on the power system stability.

Keywords: Steam turbine, Speed governor system, Regulator parameters, Power system, Damping characteristics.

1. Introduction

In recent years, with the rapid growth of the power demand in our country, the power system scale is rising and the power of the main transmission line is increasing. The operating conditions of the entire power system are becoming increasingly harsh. These lead to the occurrence of the low frequency oscillation. The low frequency oscillation has become an important factor which can restrict the power transmission and stable operation of the power grid. With several low frequency oscillation incidents which is caused by the power supply side happened recently, the study of the low frequency oscillation from power supply side gets more and more attentions. Through the analysis of the several low frequency oscillation incidents in southern power grid, the literature [1] show that there have correlation between low frequency oscillation and the instability of the steam turbine control system.

By combining the principles of the steam turbine and resonance mechanism of the low frequency oscillation, literature [2-9] analyze the possible causes of the forced power oscillation from the power supply side. The studies shown that the pressure pulsation of the turbine and the disturbance of the control valve both can lead to the forced power oscillation. The resonance mechanism of the low frequency oscillation can explain some phenomena of the low frequency oscillation. However, in order to simulate the source of forced disturbance source, a periodic disturbance was directly attached in a part of the system in the previous studies. This is not agreeing with practice situation.

Studies have shown that if some control parameters of the power supply side are set incorrectly, they can provide a negative damping torque to the system which can reduce the system damping. These will cause the low frequency oscillation of the grid [10]. Literature [11] analyzes the influence of the main parameters on the damping characteristics of the grid. Literature [12] point out that if the regulator parameters are improper, they can cause the low frequency oscillation of the Grid. But there is few research on the exactly relation between the regulator parameters and the stability of the power grid. The method to get the range of the proper regulator parameters based on transient stability analysis is also lack of research.

This paper established a mathematical model of a 600 MW steam turbine speed governor system based on practical data. Through the analysis of the steam turbine speed governor system and the power grid system, the influence of the main parameters on the damping characteristics of the grid is studied. according to the stability analysis of the system, this paper gives the range of the proper regulator parameters.

2. Modeling of Steam Turbine Governing System

Steam turbine governing system is mainly composed of controller, the electro-hydraulic servo mechanism and the steam turbine noumenon. In order to make the results closer to reality, the steam turbine governing system model parameters used to calculate in this paper come from the measured results of a 600 MW speed control system modeling.

2.1. The Controller Model

Steam turbine mode with primary frequency modulation is shown in Fig. 1.

In Fig. 1, T_l indicates time constant of speed transmitter, set the value as 0.02. K indicates the coefficient (speed range rate) of primary frequency modulation, set the value as 20. K_p, K_i, K_d indicate the *PID* parameters of load controller, set the values as 1, 0.05, 0. K2 indicates amplification coefficient of the speed feed forward control, set the value as 1. The transfer function of controller with non-linear links ignored is shown in Eq. 1, as follows:

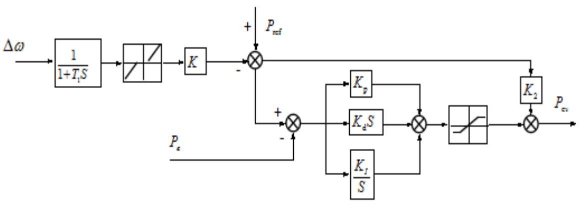

Fig. 1. The control system model.

$$G_{PID}=K_p+\frac{K_i}{s}+K_d \quad (1)$$

2.2. Electro Hydraulic Servo Mechanism Model

The instructions produced by controller finally reach electro-hydraulic servo mechanism, completing the control of the opening of the tone through the electro-hydraulic servomechanism. The model of the electro-hydraulic servo mechanism is shown in Fig. 2.

In Fig. 2, K_{p1}, K_{i1}, K_{d1} are parameters of valve controller, and the values are equal to 9, 0, 0, respectively. T_c and T_o are time constants of hydraulic servo-motor opening and closing, the parameters are equal to 1.24 and 1.33 respectively; T_2 indicates time constant of linear displacement transducer, set the value as 0.02.

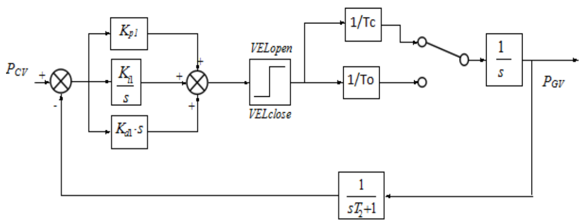

Fig. 2. The electro-hydraulic servo mechanism model.

The transfer function of electro-hydraulic servo mechanism with non-linear links ignored is shown in Eq.2, as follows:

$$G_e=\frac{(sK_p+K_i)}{T_O s^2(sT_2+1)+(sK_p+K_i)} \quad (2)$$

2.3. Steam Turbine Model

Steam turbine model is shown in Fig. 3. In Fig. 3, T_{ch}, T_{rh}, T_{co} indicate time constants of the pipe, reheater and cross tube system, set parameter as 0.1, 12, 1. F_{hp}, F_{ip}, F_{lp} indicate the share of the work produced by high, medium and low pressure cylinder in total mechanical power, set values as 0.32, 0.32, 0. (The medium and low pressure cylinder will be seemed as a whole, so the power coefficient of low pressure cylinder is set as 0). λ indicates natural adjustment coefficient of high pressure cylinder, set parameter as 0.9. The transfer function is shown as Eq.3, as follows:

$$G_T=\frac{((1+\lambda)(1+T_{\mathrm{rh}}s)(1+T_{\mathrm{co}}s)F_{\mathrm{hp}}+(F_{\mathrm{ip}}-\lambda F_{\mathrm{hp}})(1+T_{\mathrm{co}}s)+F_{\mathrm{lp}})}{((1+T_{\mathrm{ch}}s)(1+T_{\mathrm{rh}}s)(1+T_{\mathrm{co}}s))} \quad (3)$$

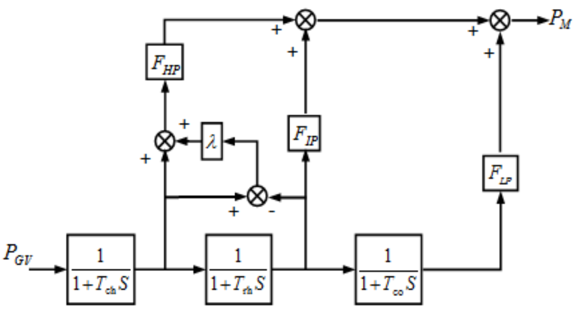

Fig. 3. Steam turbine model.

3. Single Machine Infinite System Model

Grid adopts single-machine infinite system model, as shown in Fig. 4. K_1, K_2, K_3, K_4, K_5, K_6 are the proportionality coefficients. ΔP_m indicates the mechanical power increment. ΔP_e indicates electromagnetic power increment. ΔP_{ex} indicates the excitation system power increment. $\Delta\Psi_{fd}$ indicates the excitation loop flux increment. ΔE_{fd} indicates the exciter output voltage increment. U_{pss} indicates the stabilizer output signal of power system. T_3 indicates excitation circuit time constant. T_R indicates time constant voltage sensor. $G_{ov}(s)$ indicates exciter proportion coefficient (denoted as K_A). Set values of the above parameters as the typical values [13]. The transfer function is shown in Eq.4:

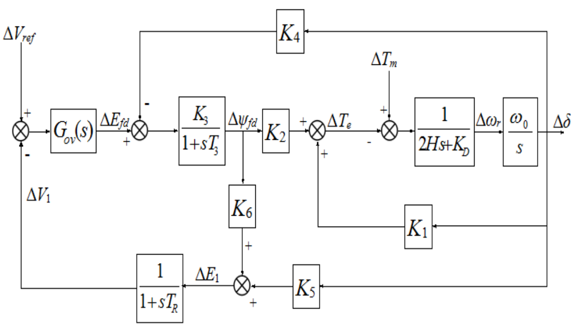

Fig. 4. Single machine infinite system model.

$$G_1(s)=\frac{\Delta P_e}{\Delta\delta}=(K_1-\frac{K_2K_3[K_4(1+sT_R+K_5K_A)]}{s^2T_3T_R+s(T_3+T_R)+1+K_3K_6K_A}) \quad (4)$$

4. Damping Analysis of the Steam Turbine Governing System

According to the Eq.1~4, the transfer function of the steam turbine governing system ignored some nonlinear link can be deduced.

$$-\Delta P_m=(\frac{1}{(1+T_1s)\delta}(1+G_{pid})+\frac{1}{s}G_1G_{pid})G_eG_t\Delta\omega \quad (5)$$

Analyze the frequency domain with the formula $s=jw$ taken into the Eq. 5:

$$-\Delta P_m = K_s\Delta\delta + K_D\Delta\omega \quad (6)$$

where K_s and K_D are the synchronization torque coefficient and the mechanical damping torque coefficient respectively. It is easy to find that the damping offered to electric power system by turbine regulating system is related with its parameters and oscillation frequency. Through the control of ΔP_m, a mechanical power (torque) is produced. if the mechanical power ΔP_m is reverse to $\Delta\omega_m$, it will increase the damping of the system. Conversely, it will weaken the damping of the system.

Take the values of the model parameters into the Eq.5, then the real part and imaginary part of the transfer function are acquired. The real part indicates the size of mechanical damping torque coefficient of the steam turbine speed governor system. Through drawing out the power system damping characteristic curve, the effect of the steam turbine control parameters have on the damping characteristics can be analyzed.

Set the value of the integral coefficient K_i and differential coefficient K_d as 0.05 and 0 respectively, and set the value of the proportional coefficient K_p to 1, 0.1, 0.5, 2 respectively. Draw out the mechanical damping torque coefficient curve, as shown in Fig. 5.

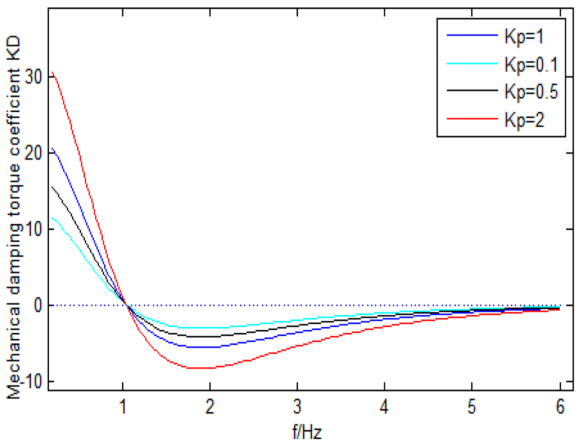

Fig. 5. Effect of K_p on mechanical damping torque coefficient.

According to the Fig. 5, it is easy to find out that the critical points of the additional damping (the damping is zero) provided by turbine speed governor system are the same. Before the oscillation frequency reaches the critical points, the additional damping provided by turbine speed governor system is positive. The larger the K_p, the greater the additional damping presented to the system. After the oscillator frequency reaches the critical point, the damping provided by the system is negative. The larger the proportional coefficient K_p, the greater the negative additional damping provided by the system. When the oscillation frequency is very high, the negative damping provided by the system tends to 0. At this point, the proportional coefficient K_p does not affect the additional damping.

Set the value of the proportional coefficient K_p and differential coefficient K_d as 1 and 0 respectively, and set the value of the integral coefficient K_i to 0.05, 0.1, 1, 2 respectively. Draw out the mechanical damping torque coefficient curve, as shown in Fig. 6.

According to Fig. 6, it is not difficult to find that the dividing frequency of the critical points decreases with the integral coefficient K_i increases. When the oscillation frequency is less than the frequency of critical point, the damping provided by the turbine speed governor system is positive, and the larger the K_i, the greater the positive damping. when the oscillation frequency is higher than the dividing frequency, the additional damping is negative. The larger the K_i, the greater the negative damping. When oscillation frequency is very high, the negative damping tends to 0, At this point, the proportional coefficient K_i does not affect the additional damping.

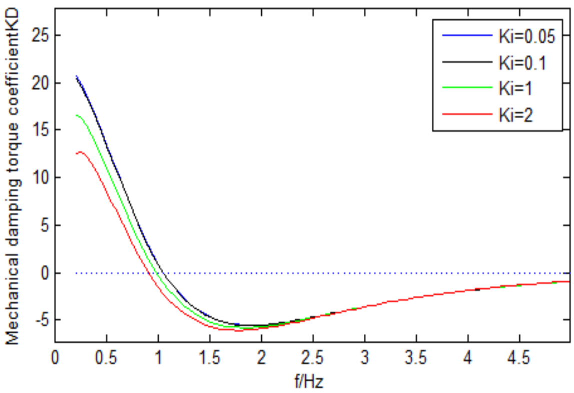

Fig. 6. Effect of K_i on mechanical damping torque coefficient.

Set the value of the proportional coefficient K_p and integral coefficient K_i as 1 and 0.05 respectively, and set the value of the differential coefficient K_d to 0, 0.1, 1, 1.5 respectively. Draw out the mechanical damping torque coefficient curve, as shown in Fig. 7.

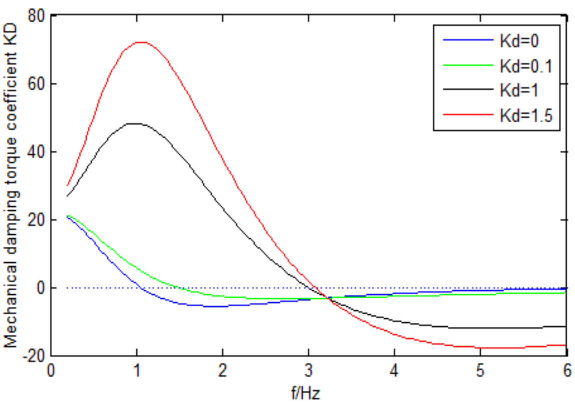

Fig. 7. Effect of K_d on mechanical damping torque coefficient.

According to Fig. 7, it is easy to find that the dividing frequency of the critical points increases with the differential coefficient K_d increases. When the oscillation frequency is less than the dividing frequency, the damping provided by the turbine speed governor system is positive. The larger the K_d, the greater the positive damping. When the oscillation frequency is higher than the dividing frequency, the additional damping is negative. When oscillation frequency is very high, the system still provides a negative damping to the grid, At this time, it is very easy to cause the oscillation of control process. Aim at this reason, the value of the differential coefficient is set as 0 usually.

Through the above analysis, the regulator parameters in steam turbine speed governor system have a significant impact on the damping characteristic of the power system. If regulator parameters are inappropriately, the damping of some oscillation mode in power grid may be deteriorated, so as to lead the happening of the low frequency oscillation in power system.

5. The Setting Method of Steam Turbine Regulator Parameters Based on Power System Stability

According to the above analysis, the turbine control system control parameters have a significant effect on the damping characteristics of the power system. However, when turning the regulator parameters in previous work, only the stability of the turbine governor system was considered, and the stability of the power system was ignored. These lead to the result that the turbine governor system can provide negative damping to the power system in some cases, then the low frequency oscillation accident is happened. So the method to turn the regulator parameters in steam turbine governor system based on the stability of power system is very important. It can prevent the low frequency oscillation accident when the unit is involved.

The transfer functions of the main parameters in the single-machine infinite bus system are shown in Eq. 7, as follows:

$$\begin{aligned}
&-\Delta P_m = \left(\frac{1}{(1+T_1 s)\delta}(1+G_{pid}) + \frac{1}{s}G_1 G_{pid}\right)G_e G_t \Delta\omega; \\
&(\Delta P_m - \Delta P_e)\frac{1}{T_\sigma s} = \Delta\omega; \\
&\Delta P_e = \left(K_1 - \frac{K_2 K_3[K_4(1+sT_R+K_5 K_A)]}{s^2 T_3 T_R + s(T_3+T_R)+1+K_3 K_6 K_A}\right)\Delta\delta \\
&\Rightarrow \frac{\Delta P_m}{\Delta\omega_r} = \frac{G_2(1+G_{pid})G_e G_t}{1+G_3 G_4}
\end{aligned} \tag{7}$$

The G_1, G_2, G_3, G_4 are defined in Eq. 8-11:

$$G_1 = (K_1 - \frac{K_2K_3[K_4(1+sT_R+K_5K_A)]}{s^2T_3T_R+s(T_3+T_R)+1+K_3K_6K_A}) \quad (8)$$

$$G_2 = \frac{1}{(1+T_1s)} \quad (9)$$

$$G_3 = (\frac{1}{(1+T_1s)\delta}(1+G_{pid})+\frac{1}{s}G_1G_{pid})G_eG_t \quad (10)$$

$$G_4 = \frac{1}{T_\sigma s + G_1\frac{1}{s}} \quad (11)$$

The necessary and sufficient conditions for the stability of the system show that all the characteristic roots of the system must have a negative real part. But the order of the characteristic equation of the system is very high, the analytic solution can't be obtained. The only way to acquire the range of the control parameters is to analysis the numerical solution.

The higher-order system can be turned into the combination of the zero order models, first order models and second order models. The oscillating component is mainly from the second order oscillation link. Through the analysis of the transfer function [Eq.5], it can be known that the zero order link don't exist in the system. The characteristic roots of the transfer function can be the nonzero roots on the real axis and complex conjugate roots. As shown in Equation 12:

$$s = A + Bj \quad (12)$$

A and B are the real part and imaginary part of the characteristic roots respectively.

The characteristic roots of the second order oscillation link are complex conjugate roots. As shown in equation 13:

$$s_{1,2} = -\xi\omega_n \pm j\omega_n\sqrt{1-\xi^2} \quad (13)$$

where ζ is the damping ratio and the ω is the undamped oscillation frequency. When the ζ is less than zero, the second order system is not stable with its real part of characteristic roots are not negative. Therefore, the damping ratio ζ can reflect the stability of the second order system. Learn from the characteristic of the second order system, the characteristic parameter ζ can be obtained when analyzing the stability of the power system. The expression of the ζ is shown in Eq.14, as follows:

$$\xi = \frac{-A}{\sqrt{A^2+B^2}} \quad (14)$$

When the characteristic roots are complex conjugate roots, their characteristic parameters ζ mean the damping ratio; when the characteristic roots are the nonzero roots on the real axis, their characteristic parameters ζ are equal to ±1. The ζ *is* equal to 1 means the real root is less than zero and The ζ *is* equal to 1 means the real root is greater than zero. When the system is stable, all the characteristic roots of the system have negative real parts, and it can be deduced that all the characteristic parameters ζ of the characteristic roots are equal to positive value. Therefore, according to the sign of the minimum characteristic parameter ζ, the stability of the system can be analyzed.

When the regulator parameters Kp and Ki are changed, the numerical solution of the characteristic parameters can be obtained through the analysis of the transfer function. Then according to the sign of the minimum characteristic parameter ζ, the stability of the system can be predicated. Through the analysis of the curve which shows the relationship between the characteristic parameters ζ and the regulator parameters, the range of the proper regulator parameters can be acquired.

The Fig. 8 shows the changing trends of the minimum characteristic parameter ζ when the regulator parameters K_p and K_i are equal to different values. If the characteristic parameter ζ is less than zero, the system is beginning to turn into instability. As shown in figure 8, when the K_p is between 0 and 4, and the K_i is between 0 and 3.1, the system may be stable. Therefore, according to the cut-and-trial method within the above range, the proper regulator parameters can be acquired.

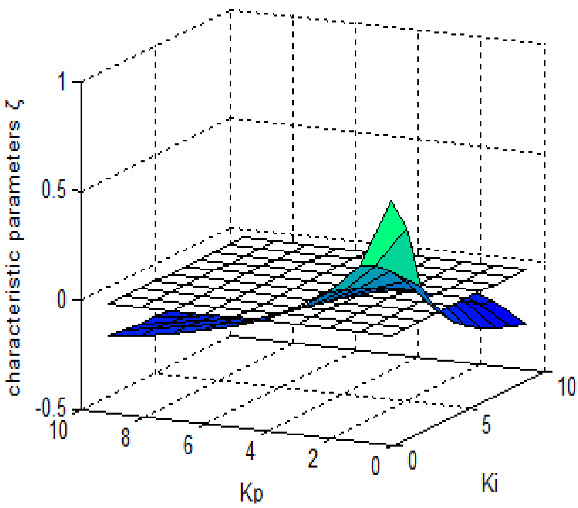

Fig. 8. The effect of regulator parameters on mechanical damping torque.

6. Conclusions

The frequency domain analysis of the mechanical damping torque coefficient indicates that the regulator parameters of turbine governor have appreciable impact on the stability of the power system, especially the power system within the low frequency range. Different regulator parameters of turbine governor have different influences on the damping characteristics of the power system, so if the regulator parameters are improper, they can reduce the damping of the system in certain low frequency oscillation modes. Through the analysis of the mechanical damping torque coefficient under the various combinations of the regulator parameters, this paper gives the qualitative trends of the system damping when the control parameters change. This can provide a useful reference for the control of the low frequency oscillation.

This paper brings forward a setting method of the steam turbine regulator parameters based on the power system stability. Through the analysis of stability of the system, the range of the proper regulator parameters can be acquired. This will have an important significance for the setting specification of the regulator parameters and the reducing of the low frequency oscillation.

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