Parameter optimization of governor for hydropower turbines to improve damping characteristics and regulation rate

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Abstract. Due to its characteristics, hydropower turbines may provide negative damping in the process of ultra-low frequency oscillation. It is necessary to improve the response of hydropower units in the process of ultra-low frequency oscillation by adjusting the PID parameters reasonably. Although the adjustment of PID parameters can significantly improve the damping characteristics of hydropower turbines, it will sacrifice a certain speed of regulation, which is not conducive to the primary frequency regulation of the system. Through the establishment of the hydroelectric turbines model, the damp and regulating speed are optimized as the control objectives, so that better parameters can be obtained to suppress the ultra-low frequency oscillation of the system.

1. Introduction

Some high-proportion hydropower areas are asynchronously connected to the main grid through HVDC. The capacity of hydropower can reach 60% of the total capacity in these areas. This has raised the influence of regulation performance and dynamic characteristics of hydropower units to the stability of the power grid.

After the asynchronous interconnection, the negative damping characteristics of some generator speed control systems will be fully exposed, and the fast regulation speed control system will bring obvious negative damping, which will lead to periodic fluctuation of power system frequency. When the damping is weakened, the fast regulation of speed control system will lead to a period increase or equal-amplitude oscillation of system frequency, which will lead to instability of system frequency and large generator, which will bring great risks to the operation of power grid. After the asynchronous operation of power grid, the moment of inertia decreases, and the frequency oscillation caused by improper parameter configuration of speed control system occurs\(^{[1,2]}\).

When the ultra-low frequency oscillation occurs, the frequency of the system varies greatly in a long period, which is strongly related to the primary frequency regulation performance of the turbine governing system and the "water hammer effect" of the water diversion system. When the ultra-low frequency oscillation occurs, the governing system operates periodically and frequently, and the frequency of the system varies greatly. However, the excitation system and PSS have no obvious response to the oscillation, and their properties are obviously different from those in the conventional sense\(^{[3]}\).

Due to the small inertia of the asynchronous connection between local grid and the main grid, the frequency stability of the system is closely related to the primary frequency modulation performance of the governor. In order to improve the damping level of the power grid with high hydropower ratio in ultra-low frequency band, it is necessary to adjust the PID parameters of the governor. However, small parameters will significantly reduce the primary frequency modulation performance, which is not conducive to frequency recovery after large disturbance. Therefore, the PID parameters of the
governor need to be balanced between the primary frequency modulation performance and the suppression of ultra-low frequency oscillation. There is an urgent need to study the parameter adjustment scheme of the speed control system of hydropower units to lay a foundation for the follow-up study of frequency stability characteristics and related preventive and control measures, and ensure the safe and stable operation of the asynchronous networked outgoing transmission system.

This paper is organized to discuss the parameters to meet the requirements of ultra-low frequency oscillation damping, and the regulation rate of the system will not be too slow.

2. Ultra-Low Frequency Oscillation Mechanism

2.1. Water hammer effect

Because of the inertia of water, the flow rate will not change immediately when the guide vane opening changes. In the initial stage of turbine guide vane change, the direction of the initial impact of active power is opposite to that of the guide vane position change: when the guide vane is opened, the power decreases due to the decrease of pressure; when the guide vane is closed, the power increases due to the increase of pressure. The turbine power is finally approximated to the guide vane control instruction according to the water hammer time constant $T_w$.

$$\Delta P_v(t) = [1 - 3e^{-2\pi T_w/\omega}]\Delta G$$  

(1)

These characteristics of hydraulic turbines lead the hydropower units to a "non-minimum phase system". During the period of system decoupling or isolated operation of hydropower units, the unstable control of hydropower turbines may lead to the unstable frequency of power grid, that is why the ultra-low frequency oscillation occurs.

2.2. Turbine Governing System

The following figure 1 shows the governor of a certain type of hydropower unit. Opening mode and power mode can be selected when connected. When the frequency deviation is large, the governor can be converted to isolated network mode[4].

![Figure 1. Turbine Governing System](image)

In power mode, the power signal is ignored and only the speed signal is considered. The transfer function of the regulating system is as follows:

$$G_1 = \frac{1}{\epsilon_g} \left( K_p + \frac{K_{p1} s}{1 + T_{p1} s} + \frac{K_{p2}}{s} \right)$$  

(2)
In the opening mode, the transfer function of the regulating system is as follows:

$$G_s = \frac{K_p \left( \frac{K_{p2}}{1 + T_{e2}s} + \frac{K_{p3}}{s} \right)}{1 + B_p \frac{K_{i2}}{s}}$$

(3)

The transfer function of the hydraulic system is:

$$G_h = \frac{\left( K_p + \frac{K_{i2}}{s} + \frac{K_{i4}}{s} \right) \frac{1}{T_s}}{1 + \left( K_p + \frac{K_{i2}}{s} + \frac{K_{i4}}{s} \right) \frac{1}{T_s}}$$

(4)

The model of the turbine is as follows:

From equation (2), ignoring the nonlinear parts then the transfer function can be written as:

$$G_s = \frac{1-aT_p s}{1+bT_p s}$$

(5)

By substituting $s=j\omega$ to the transfer function, the damping coefficients of the governor and the prime motor can be calculated.

3. Analysis of Damping Characteristics in isolated network mode

3.1. Damping Characteristics

$$G = G_{gov} G_{hydro}$$

$$\Delta P_m = D_e \Delta \omega + jT_m \Delta \omega$$

(6)  (7)

From the transfer function between $\Delta P_m$ and $\Delta \omega$, it can be seen that the generator will provide positive damping to the system when $D_e > 0$. And from the analysis on the damping characteristics of hydropower turbine governing system and the open-loop transfer function of the prime motor. The torque provided by the governing system is projected onto the $\omega$ axis, i.e. the damping torque component provided by the governing system is defined as the damping coefficient of the governing system, so as to evaluate the damping performance of the governing system[5-6].

The simplified model of typical turbine governing system can be expressed as follows:

$$G = \frac{K_u \left( K_{p1} + \frac{K_{i2}}{1+T_{i1}s} + \frac{K_{i4}}{s} \right)}{1 + B_p \frac{K_{i2}}{s}} \frac{K_{p2} + \frac{K_{i2}}{s} + \frac{K_{i4}}{s}}{sT_o \left( 1 + T_s \right)} + \frac{K_{p3} + \frac{K_{i2}}{s} + \frac{K_{i4}}{s}}{1 + 0.5T_s}$$

(8)

$$\Delta P_m = G(s) \Delta \omega$$

$$D_e = \text{Re}[\Delta P_m (j\omega)]$$

(9)  (10)

The hydropower governing system has obvious phase lag effect in low frequency band. As shown in the table 1 below, the hydropower governing system with typical parameters provides negative damping in the range of 0.01-0.1Hz.

The phase-frequency and amplitude-frequency characteristics of the governor system can be adjusted by modifying the PID parameters of the governor. The time constant of hydraulic hammer has a great influence. The oscillation can be alleviated by adjusting the PID parameters of governor, but a certain adjusting speed will be sacrificed[7].
Table 1. Phase and amplitude at different frequencies

| Oscillation frequency (Hz) | Amplitude | Phase  |
|----------------------------|-----------|--------|
| 0.01                       | 24.63     | -28.19|
| 0.02                       | 23.63     | -55.51|
| 0.03                       | 22.29     | -71.38|
| 0.04                       | 20.85     | -85.58|
| 0.05                       | 19.48     | -98.16|
| 0.06                       | 18.26     | -109.28|
| 0.07                       | 17.19     | -119.14|
| 0.08                       | 16.28     | -127.93|
| 0.09                       | 15.5      | -135.8 |
| 0.1                        | 14.83     | -142.89|

3.2. Sensitivity of PID parameters related to ultra-low frequency oscillation

By adjusting $K_p$, $K_i$, $K_d$ and $B_p$, the damping changes in low frequency band could be observed. When $K_p=3$, $K_i=1$, $K_d=1$, $B_p=0.04$, the system will provide negative damping in the frequency band of 0.03-0.1, which is not enough to resist ultra-low frequency oscillation.

![Graph of damping characteristics](image)

Figure 3. The damping characteristic with $K_p$, $K_i$, $K_d$, $B_p$

As shown in figure 3, $K_p$ has a great influence on the system damping, and the increase of $K_p$ will increase the negative damping section significantly. When $K_i$ increases, the negative damping of the system will also increase significantly in the ultra-low frequency band. When $K_d$ and $B_p$ increase, a bit of positive damping may be provided.
4. Research of PID Parameters Optimization

In order to improve its ultra-low frequency damping characteristics, an optimization method is used to configure the PID parameters. Since the damping characteristics of the system in ultra-low frequency band are the most concerned, so the frequency band mainly considered in the study is $0 < f < 0.1$ Hz. And the constants of the control system is shown in table 2.

| Table 2. Constants of the Control system |
|---|---|---|---|
| T2 | Tw | Td | T0 |
| 0.08 | 2 | 1 | 14.37 |
| Kw | Kp2 | Ki2 | Kd2 |
| 1 | 10 | 0 | 0 |

Let $K=[K_p, K_i, K_d, B_p]$ be the variables with the range $[1 0 1 0.04]$ to $[10 5 3 0.2]$. Considering the ultra-low frequency oscillation does not stay at a fixed frequency, the control target can be chosen as the integral of the system damping in the frequency band. When the integral value is large, it shows that the damp of the system is generally high in the frequency band. At the same time, the lowest point of damping can be chosen as the auxiliary control target to prevent excessive negative damping $[8]$.

\[
y_1 = \int_0^{0.1} \xi df \\
y_2 = -\min(\xi)
\]

\hspace{1cm} (11)

In order to improve the performance of primary frequency modulation, the adjusting time $T_s$ of the system can be taken as the controlled variable, and the adjusting speed can be guaranteed while taking into account the damping characteristics of the system. And the max adjusting time is multiplied by a penalty factor, so that the adjustment speed will not too slow.

\[
y_3 = T_s \\
y_4 = \text{flag}(T_s \geq 60s)
\]

\hspace{1cm} (12)

Then the function is:

\[
\text{Arg}=\text{argmin}(w_1*y_1 + w_2*y_2 + w_3*y_3 + w_4*y_4)
\]

\hspace{1cm} (13)

In equation 13, weights: $w_1 = 5$, $w_2 = 1$, $w_3 = 0.05$, $w_4 = 100$. By optimizing calculation, a series of parameters can be found.

The optimized PID parameters are $K_p=2.0221, K_i=0.5723, K_d=1, B_p=0.2, T_s=36.87s$.

Figure 4 shows the damp-frequency characteristics between initial parameter and the optimized values. The damp has raised at the low frequency band, and the negative damping range has reduced.
5. Summary
Because of its own characteristics, hydropower units may produce negative damping in ultra-low frequency band, resulting in poor dynamic performance of the system. Through the optimization above, the damping characteristics of hydropower units in ultra-low frequency band can be improved, the ultra-low frequency oscillation can be suppressed, and the stability of the system can be improved. In the power grid with high hydropower proportion, more research and optimization should be considered to improve the operation status of hydropower units.

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