Experimental study and parametric analysis for primary frequency regulation of hydropower unit

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Abstract. With the integration of new large-scale energy sources into grids, power system stability is facing huge challenges. The primary frequency regulation of hydropower generators is an important regulation method for grid frequency stability and power balance. It can effectively suppress the grid frequency fluctuations caused by the high proportion of new energy sources, and it plays a very important role in maintaining the stability of the power system. The regulation parameters of the primary frequency regulation of a hydropower unit have a significant impact on its regulation capabilities and performance indices. The experimental analysis of the effects of the regulation parameters is crucial for the safe and stable operation of a hydropower unit. A frequency regulation parameter test on a hydropower station was conducted in this study to determine the effects of the regulation parameters on the performance of the primary frequency regulation. This provides a reference for the selection of the regulation parameters of a hydropower unit.

Keywords: hydropower; energy; governor; primary frequency regulation; PID parameters

1. Introduction

Primary frequency regulation (PFR) is important to ensure the stability of the grid frequency and power [1]. Primary frequency regulation can quickly provide power support in the event of sudden large load changes in the grid, improve the stability and safety of the grid operation, reduce the fluctuations of the grid frequency, enhance the grid anti-accident ability, and improve the power quality of the grid [2–4]. The primary frequency regulation performance of the speed-governor system of a hydropower unit, an important frequency-regulated power source, has a crucial impact on the safety and the electric power quality of the power grid [1]. At present, China’s power grid dis-patching agencies require grid-connected hydropower generator speed-governor systems to have a primary frequency regulation function, and they impose strict requirements on the primary frequency regulation performance of the hydropower generator speed-governor systems [5]. Studying the effect of the primary frequency regulation parameters of hydropower units has important practical value for improving the operation of hydropower units.

As a basic function of a hydropower unit and with the inherent static frequency characteristics of a hydro-turbine governing system (HTGS), primary-frequency speed-governor systems autonomously adjust the guide vane opening or active power according to the system frequency change, thereby controlling the system frequency and allowing each unit to reasonably share the load. During the generating operation of the unit, when the system frequency change exceeds the artificial frequency deadband set by the governor, the governor system changes the guide vane opening according to the set difference rate, which causes a change of the unit active power.

At present, many researchers have studied the primary frequency regulation of hydropower generator speed-governor systems mainly in the following aspects: (1) For dynamic response analysis and stability, Guo et al. [1] studied the modeling and dynamic response control for PFR of HTGS with surge tank. Yang et al. [6] built a suitable model of HTGS for conducting simulation to investigate response time for PFR of HTGS, and the new proposed formula can help to predict the power response and supply a flexible guidance of parameter tuning. Zhang et al. [7] proposed a new model of hydropower units to simulate the dynamic performance of the PFR system, and studied on the stability of PFR of hydropower units. Ref [8] focused on the dynamic response characteristics of PFR of...
pumped storage unit under different water heads and different frequency disturbances by numerical simulation. Guo et al. [9] investigated the stability and nonlinear dynamic performance of PFR of the nonlinear HTGS based on the stable domain under two different power control modes. (2) For control strategy, Fu et al. [10] proposed a multi-objective optimization strategy of PFR for hydropower unit considering ultra-low frequency oscillation, the simulative results showed that the proposed strategy can not only strengthen dynamic performance of PFR, but also suppress ultra-low frequency oscillation. Shi et al. [11] established an optimization objective function and proposed intelligent algorithm for optimal parameter. Zhang et al. [12] analyzed the problems of the control system under the power closed-loop mode, and proposed a new control strategy based on the opening-power nonlinear feedback, which has a fast response to the grid frequency regulation. Ref [13] proposed a robust control strategy to reduce frequency deviations for pumped storage generators. From the statistical aspects, Ref [14] applied the conventional generator droop control in PFR, which is beneficial to improve the system frequency stability. (3) For experimental investigation and performance evaluation, an et al. [15] developed a new frequency dead zone whit feed-forward control to achieve a comprehensive performance assessment of PFR, which can improve the economic benefit of hydropower plants. Fu et al. [16] investigated factor of influence on electricity contribution for PFR of hydropower unit, which has an important guiding significance for the optimal operation of hydropower unit. Yang et al. [17] studied wear and tear of turbines by numerical simulation and theoretical derivation considering primary frequency control with the increasing intermittent renewable energy. Hamed Delkhosh et al. [18] proposed a new technical primary frequency valuation index for the generating units and a new general frequency profile for the incidents, and then introduced the concept of weighted average of frequency active power change.

The stability of a hydropower unit worsens due to the inertia of water flow. To ensure the stability, their regulation systems need different regulation parameters under different operating conditions [19]. When operating in a single mode, the hydro-power speed-governor system parameters mainly consider the stability of the control system. When operating in parallel with a large power grid, the speed-governor system parameters are selected mainly to achieve the rapid action of the governor system [20]. When the hydropower unit adjusts the output of the unit through frequency regulation, the opening and closing of the water guiding mechanism can generate water hammer in the pressured water pipe or lead to the water hammer effect [21]. To limit the maximum change of the water pressure in the pressurized water diversion pipe, the motion speed of the water guiding mechanism must be limited. In addition, due to the large intrinsic time constant of the governor of a hydropower unit, the response speed to frequency differences is low, and the initial response presents an undesirable reverse regulation phenomenon [22]. Determining how to adopt reasonable regulation modes and parameters while taking into account the stability and rapid movement of the hydropower unit control system and how to ensure that the power is not reversed during the first frequency adjustment is of important practical value for the efficient and stable operation of hydropower units. Through field tests, the effects of the primary frequency regulation parameters on the regulation performance were examined in this study, and reliable regulation parameters for the operation of hydropower units are provided to ensure the efficient and stable operation of the units.

The content of this paper is organized as follows: Section 1 presents the research background, the motivations and objectives of this paper. Section 2 introduces the mathematical models of regulation system and engineering model of field test. In Section 3, method and performance index were presented. In Section 4, the results are shown. Finally, Section 5 describes the conclusions of this paper.

2. Model

2.1. Mathematical Model

A hydro-turbine governor mainly consists of two parts: a controller and a hydraulic servo system, as shown in Fig.1. The parallel PID (proportional integral differential) control model is usually applied here. Its transfer function is shown in equation (1). The transfer function servo system model is shown in equation (2):
\[ G_{PID}(s) = \frac{(K_P T_D + K_D)s^2 + (K_P + K_I)s + K_I}{(K_P T_D b_p + K_D b_p + T_D)s^2 + (K_P b_p + K_I T_D b_p + 1)s + K_I b_p} \]  

(1)

\[ G_{servo}(s) = \frac{1}{T_y T_s s^2 + T_s s + 1} \]  

(2)

In the model, \( f \) is the unit frequency; \( C_f \) is the given value of the target frequency; \( E_f \) is the unit frequency regulation dead zone; \( K_P \) is the proportional gain; \( K_I \) is the integral gain; \( K_D \) is the differential gain; \( T_D \) is the differential time constant; \( b_p \) is the permanent difference coefficient; \( T_y \) is the pure delay time of the servo system; \( T_s \) is the servomotor time constant; \( S \) is a Laplace operator; \( v_{\text{max}} \) is the highest opening speed of the servomotor; \( v_{\text{min}} \) is the highest closing speed of the servomotor; \( y_{\text{max}} \) is the upper limit of the servomotor, which is in a fully open position in most cases; and \( y_{\text{min}} \) is the lower limit of the servomotor, which is in a fully closed position in most cases. \( E_p \) is the unit power regulation dead zone. \( e_p \) is the power difference coefficient. \( P_c \) is the set value of the power, and \( P_G \) is the measured power value of the hydro-generator unit. As shown in Fig.1, \( K_D \) and \( T_D \) are equal to zero, and equation (1) can be simplified to equation (3):

\[ G_{PI}(s) = \frac{K_P s + K_I}{(K_P b_p + 1)s + K_I b_p} \]  

(3)

![Figure 1. Structure of the mathematical model of hydro-turbine governor](image)

### 2.2. Engineering Model

A field test was carried out on the hydro-generator unit in a real hydropower station in China, and the main parameters of the test unit are listed in Table 1. The test data were obtained from the data acquisition system of the unit governor. The data collected in real time mainly included the frequency, power, and set power of the hydro-generator unit, and the guide vane opening.

| Main Parameters | Value |
|-----------------|-------|
| Turbine model   | HL-LJ-630 |
| Rated water head| 44 m  |
| Rated speed     | 93.75 r/min |
| Rated output    | 142.90 MW |
| Rated flow rate | 352.57 m³/s |
Figure 2 shows the hydropower unit speed-governor field equipment used in our study. The equipment includes an electrical control system and a hydraulic servo system. The electrical control system mainly includes the controller and its circuits. The hydraulic servo system is mainly responsible for executing the instructions of the electrical control system.

![Figure 2. hydro-turbine governor](image1)

3. METHOD AND PERFORMANCE INDEX

3.1. Method

Figure 3 shows the equipment used in the field test, including the emulator and software for the turbine governor system test. The test steps were as follows:

![Figure 3. Field test equipment](image2)

(1) In automatic opening adjustment or power adjustment mode, the governor performed a primary frequency regulation function. The unit operated at a steady state at 60%–90% of the rated power.

(2) A frequency signal similar to the actual grid frequency disturbance process was applied to the governor through the frequency signal source of the tester. The absolute value of the effective frequency deviation should not be less than 0.1Hz. The changes of various signals, such as the frequency of the source signal, the regulator control output, the servomotor stroke, the active power of the unit, and the water pressure, were recorded.

(3) The governor was switched to the manual state, the output line of the frequency signal source was disconnected, the actual frequency signal of the governor was re-stored, and the governor was returned to the automatic state after confirming that there was no error. The frequency regulation
function was started, and the artificial frequency/speed deadband was set to 0–0.05 Hz. The changes of the unit frequency, regulator control output, servomotor stroke, active power of the unit, and water pressure when the actual grid frequency changed were recorded. The test recording time was not less than 10 min.

(4) The measured unit power response curve was used to obtain the actual integral power $Q_a$ during frequency regulation, and it was divided by the theoretical integral power $Q_{th}$ to obtain the integral power ratio $R_m$.

3.2. Performance Index

The engineering performance index under stable operating conditions of the hydropower units with a load and a frequency step disturbance whose absolute value was not less than 0.1Hz, Figure 4 shows responses to the primary frequency steps. The requirements are as follows:

(1) The power response retardation time $t_h$, from the time that the frequency difference exceeds the deadband of the primary frequency regulation to the time that the active power of the unit starts to change to the target power should not be greater than 6 s for hydropower units with a rated waterhead of 50 m and greater; it should not exceed 10 s for hydropower units with a rated waterhead of less than 50 m.

(2) The rise time $t_9$, from the time the frequency difference exceeds the deadband of the primary frequency regulation to the time the unit’s active power reaches 90% of the target value should not be greater than 20 s.

(3) The time $t_s$ from when the frequency difference exceeds the deadband of the primary frequency regulation to when the power regulation reaches the stable deviation band $\delta_r$ should not exceed 45 s.

(4) The principle of determining the stable deviation band $\delta_r$ is as follows. For the same position of the servomotor, where the unit’s own power continuously fluctuates for 3 to 6 min, if the peak-to-peak value does not exceed 1.5% of $K_r$, then $\delta_r = 1.5\% P$; if it exceeds 1.5% of $P$, then the maximum peak-to-peak value is taken as $\delta_r$.

![Figure 4. PFR power response process: (a) downward frequency disturbance and (b) upward frequency disturbance.](image-url)

The primary frequency regulation integral power ratio $R_m$ should be calculated as follows:

$$R_m = \frac{Q_a}{Q_{th}} = \frac{\sum (P_r - P_s)}{\sum P_r \times \frac{Af(t)}{f_r} \times \frac{1}{e_r}}$$ (4)
where \( Q_a \) is the actual integral power, \( Q_m \) is the theoretical integral power, \( \Delta f(t) \) is the effective frequency deviation, \( P_r \) is the rated power of the unit, \( f_r \) is the rated frequency, \( e_p \) is the compensation ratio, \( P_t \) is the unit’s instantaneous value of the active power, \( P_0 \) is the initial steady-state reference value of the active power of the unit before the primary frequency regulation action, \( t \) is the integral interval (1 s), and \( n \) is the integral time in the range of \( 16 \, s < n \leq 60 \, s \).

In equation (4), the effective frequency deviation, \( \Delta f(t) \), should be calculated and defined as follows:

\[
\Delta f(t) = \begin{cases} 
  0, & 0 < f_r - f_j(t) < |E_i| \\
  f_r - f_j(t) - |E_i|, & |f_r - f_j(t)| \geq |E_i| \\
  f_r - f_j(t) + |E_i|, & f_r - f_j(t) \leq -|E_i| 
\end{cases}
\]

(5)

where \( f_r \) is the rated frequency, \( f_j(t) \) is frequency taken from the generator outlet, and \( E_i \) is the artificial frequency or speed deadband. The transient frequency, \( f_j(t) \), should be measured at a point at the generator outlet and should not be replaced by the frequency measured on the high voltage side of the main transformer or at other locations in the power grid.

The principle of selecting the initial steady-state reference value \( P_0 \) of the active power of the unit before frequency regulation starts in equation (4) is as follows. The AGC target power is represented by \( P_0 \). If the duration of the primary frequency regulation recovery time is more than 20 s, the average of the measured value of the active power during this period can also be considered to be \( P_0 \). From the time the frequency difference \( f_r - f_j(t) \) exceeds the artificial deadband \( E_i \) of the primary frequency regulation to the end of the primary frequency regulation adjustment process of the hydropower units, the integral power ratio of the primary frequency regulation should not be less than 30%. From the time the frequency difference \( f_r - f_j(t) \) exceeds the artificial deadband \( E_i \) of the primary frequency regulation to the end of the primary frequency regulation adjustment process of the hydropower units, if the frequency deviation duration does not exceed 16 s or the maximum effective frequency difference \( \Delta f(t) \) does not exceed 0.003 Hz, the primary frequency regulation integral power ratio \( R_{th} \) obtained from Equation (4) should not be used as the basis for assessment.

4. RESULTS AND ANALYSIS

4.1. Effect of \( K_p \) on Primary Frequency Regulation Characteristics

The proportional gain \( K_p \) was used to adjust the actual error, and it had good adjustment sensitivity. At \( H = 44 \, m \) and \( P = 80\% \), the frequency increased by 0.2 Hz, and the integral time constant \( K_I = 4 \). The response characteristics under different proportional gains \( K_p \) are shown in Figures 5, 6, and 7.

Figure 5. Dynamic response characteristics with \( K_p = 3 \) and \( K_I = 4 \).
As evident from the response characteristics, for the same the integral time constant $K_I$, increasing the proportional gain $K_p$ accelerates the adjustment speed. However, too great of a $K_p$ would produce overshoot or even cause system oscillations. Conversely, a decrease in $K_p$ would reduce the control amount and increase the stability of the regulation system, but the regulation speed would be slow.

Increasing $K_p$ increases the response speed. From this aspect, the integral power ratio can be increased. However, a large $K_p$ would cause the reverse regulation power and the duration to increase, which would cause the retardation time of the first frequency regulation to increase, and it could reduce the integral power ratio.

4.2. Effect of $K_I$ on Primary Frequency Regulation Characteristics

$K_I$ is mainly used to eliminate static errors and improve the adjustment accuracy of the system. At $H = 44$ m and $P = 80\%$, the frequency rise was 0.2 Hz and $K_p = 6$. The response characteristics at different integral time constants are shown in Figures 8, 9, and 10.
Figure 8. Dynamic response characteristics with $K_p = 6$ and $K_I = 2$.

Figure 9. Dynamic response characteristics with $K_p = 6$ and $K_I = 4$.

Figure 10. Dynamic response characteristics with $K_p = 6$ and $K_I = 6$.

As evident from the response characteristics, a larger $K_I$ may lead to over-adjustment and cause the system to oscillate near the equilibrium point. The proportional gain can be appropriately decreased to reduce the adjustment speed, and thus, the response characteristics meet the requirements for speed and sensitivity. Conversely, a smaller $K_I$ leads to a weak integral effect, and the static error is eliminated slowly. In this case, $K_p$ can be increased appropriately to increase the adjustment speed and enhance the ability to prevent overshoot. Thus, its response characteristics meet the requirements of speed and sensitivity.
A larger $K_P$ may cause overshoot and oscillations of the system. $K_I$ can be set to a smaller value to weaken the integral effect, so that its response characteristics can meet the requirements of speed and sensitivity. Conversely, a smaller $K_P$ leads to low adjustment speed. $K_I$ can be set to a larger value to enhance the integral effect and increase the elimination speed of steady-state errors. Thus, the response characteristic can meet the requirements for speed and sensitivity.

Combined with the later performance indicator analysis, it can also be shown that as $K_I$ increases, the speed of eliminating steady-state error increases, and the integral power ratio increases. However, as mentioned earlier, an excessively large $K_I$ will cause overshoot and even oscillations.

4.3. Effect of $\varepsilon_p$ on Primary Frequency Regulation Characteristics

$\varepsilon_p$ is the compensation ratio. It is defined as the negative number of the slope at a certain specified operating point on the static characteristic curve of the grid frequency and the active power of the hydraulic turbine regulation system.

$$\varepsilon_p = -\frac{d\Delta f}{d\Delta P}$$

(6)

According to this equation, a smaller $\varepsilon_p$ corresponds to a greater active power adjustment at the same frequency difference. However, if $\varepsilon_p$ is too small, due to the excessive adjustment of the active power of the hydropower unit, unstable operation of the unit can occur. At $H = 145$ m, $P = 80\%$, and a frequency change of $\pm$ 0.1 Hz, $K_P = 6$ and $K_I = 4$. Ignoring the feedforward, the effects of different on the primary frequency regulation are shown in Figures 11, 12, and 13.

**Figure 11.** Dynamic response characteristics with $\varepsilon_p = 2.5$.

**Figure 12.** Dynamic response characteristics with $\varepsilon_p = 1$. 
Based on the response characteristics, with a gradual decrease in $\epsilon_{e}$, the adjustment amount of the active power gradually increases during the adjustment process. However, too small of an $\epsilon_{e}$ would cause overshoot. Therefore, the smaller $\epsilon_{e}$ is, the larger the adjustment of the active power becomes for primary frequency regulation. Thus, $\epsilon_{e}$ cannot be too large or too small.

5. Conclusions and discussions

(1) The major factors that determine the strength of the primary frequency regulation function are the differential rate (or permanent speed droop), speed deadband, and proportional and integral gains. Increasing $K_{p}$ and $K_{i}$ significantly increases the electrical contribution of the primary frequency regulation. Increasing $\epsilon_{e}$ significantly decreases the electrical contribution of the primary frequency regulation.

(2) Due to the adverse water hammer effect caused by the inertia of the water flow, a hydropower unit has a reverse regulation problem in the beginning of the load adjustment process, which affects the effectiveness of the unit’s primary frequency regulation.

(3) The primary frequency regulation parameters of a hydropower unit should be set and determined through parameter analysis and field testing.

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