Study on the Strategy of Improving the Primary Frequency Regulation Capability by Adaptive Parameters of Turbine Governor

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Abstract. Many studies have shown the inverse regulation characteristics of water hammer effect inherent in the hydropower system and the unreasonable parameter configuration of the governor result in the generation of the ultra-low frequency oscillation. The main research work of this paper is above two points. Based on the detailed analysis of the influence of each parameter of the speed regulating system on the frequency characteristics of primary frequency regulation, combining with the improved particle swarm optimization algorithm, a self-adaptive parameter configuration technology on PID governor of hydraulic turbine regulation system is presented, the PID parameters can be adjusted continuously according to the rotation speed deviation. And the simulation analysis is carried out. The effectiveness of the adaptive PID parameter method to improve the primary frequency regulation ability is verified.

1. Introduction

The installed hydropower of Southwest Power Grid has accounted for about 70% of the total installed power grids. Its maximum absorption of clean hydropower occurs in high water period, and the hydropower output takes up over 80% under the typical operation mode. Due to the asynchronous interconnection, the reduction of the system moment of inertia requires the generator speed regulating system to adjust the active power output in a much faster and deeper way, which will induce periodic frequency fluctuations in the power system. When the damping is weakened, the excessively fast speed regulation system will then lead to the ultra-low frequency oscillation of the system; in severe cases, it will cause large-scale off-grid of the generating units, even leading to the loss of system frequency stability, which will bring great risks to the safety and stability of the power grid operation.[1-3] In terms of the field measures of oscillation suppression and the follow-up research results, there is a strong correlation between ultra-low frequency oscillation and primary frequency regulation control process. Therefore, studying the influence of hydroelectric speed regulation system on the stability of primary frequency regulation and taking effective measures to suppress the ultra-low frequency oscillation are of great significance to ameliorate the primary frequency regulation capability. After the actual oscillation occurs, the first measure that needs to be taken is to withdraw a certain proportion of large capacity hydropower units governor, or to optimize governor PID parameters.[4-6]
At present, most of the PID parameters of the hydropower unit speed regulation system are still tuned by the traditional PID law or the optimized control law. Intelligent control theory is also applied to the optimization of hydropower unit speed regulation system. Though the fuzzy control theory is applied to the optimization of PID parameters in the previous research [7], it is difficult to avoid the decrease of control precision after fuzzy processing due to the limitation of its level of quantification; on the other hand, the calculation time will be prolonged if the quantization level is increased. Some studies used the Genetic algorithm to find the optimal solution of PID parameters through selection, crossover and mutation. [8-9] However, premature convergence may occur if the above operators are not properly selected. The current research combined the two intelligent control theories to optimize the PID parameters gradually, while forming the intelligent compound control to reduce its limitation.

The present paper focuses on the power grid system with high hydropower ratio, aiming at investigating the control characteristics of the hydroelectric speed regulation system in the primary frequency regulation process, analyzing the influence of the parameters on the primary frequency regulation while optimizing the self-adaptive parameter configuration method is optimized, so that the parameters can be changed dynamically in the regulation process, so as to better meet the requirements of the different stages of the disturbance and to improve the primary frequency regulation capability of the system.

2. Influence analysis of speed regulating system parameters on primary frequency regulation

2.1. Analysis model of multi-machine system

Considering that in the single machine system, it is difficult to know the influence factors of primary frequency regulation and the actual law of influence completely and reliably, the deviation of rotating speed of all units can be uniformly expressed by \( \Delta \omega \) when the ultra-low frequency oscillation occurs. Based on the equivalent method of multi-machine system proposed in literature [10], the present chapter established the model of multi-machine equivalent system in the process of primary frequency regulation.

The open-loop transfer function of the frequency model of the equivalent single-machine system can be written as:

\[
Q(s) = \frac{\sum G_{G0i}(s)}{s \sum T_i + K_i \sum P_{ei} + \sum D_i}
\]

Fig.1 contains the total system generator moment of inertia \( \sum T_i \), system load frequency regulation effect coefficient \( K_i \), active load rating \( P_{ei} \), generator damping coefficient \( D_i \), total mechanical power variation \( \Delta P_m \), and the transfer function of the speed regulating system \( G_{G0i}(s) \), which differentiates the type and number of generators participating in the primary frequency regulation of the whole power grid.

The open-loop transfer function of the frequency model of the equivalent single-machine system can be written as:
2.2 Influence of PID parameters on speed regulating system

In the course of primary frequency regulation, the negative damping characteristics of the hydraulic turbine and its governor may induce the problem of ultra-low frequency oscillation. In comparison with steam turbines, the mechanical power of hydraulic turbines in the simulation of dynamic characteristics has a counter-regulation process when the governor starts to operate, that is, the water hammer effect. Because of the existence of water hammer effect, there are significant differences between damping characteristics of water turbine and steam turbine. Compared with steam turbine, hydraulic turbine has significant sag in the ultra-low frequency band; its negative damping characteristic is more prominent, and the ultra-low frequency oscillation is easier to occur in hydraulic turbine.

The time constant of water hammer effect is mainly affected by the inherent length of the water intake pipe and the height of the water pressure at the guide blade of the turbine. The PID control parameter of the speed regulating system is analyzed here since there are difficulties carrying on the adjustment control. On the basis of the actual ultra-low frequency oscillation data, the impact of parameters on the ultra-low frequency oscillation frequency, damping torque coefficient and the degree of oscillation participation are analyzed by controlling parameter variation.

In Fig.2, the influence of the proportional magnification factor $K_P$ is discussed. While other control parameters remain unchanged, with the increment of $K_P$, the oscillation frequency increases; the damping level decreases rapidly; the degree of $K_P$ participating in the oscillation rises.

![Fig.2. Influence analysis of variation of $K_P$](image)

In Fig.3 the variation of the Integration magnification factor $K_I$ has almost the same trend as that of $K_P$.

![Fig.3. Influence analysis of variation of $K_I$](image)

In Fig.4 it can be seen that the damping property of $K_D$, which is different from $K_P$ and $K_I$, appears an inflection point. Before the inflection point, with the increase of $K_D$, both the oscillation frequency and the negative damping level of the system increases; the effect of $K_D$ on the oscillation declines.
However, as the value of $K_D$ crosses the inflection point, the damping level of the system changes from negative to positive and gradually decreases. The variation of the PID parameters makes it possible to let the damping characteristic of the system in the ultra-low frequency band be negative when the PID parameters are not properly configured. In the high hydropower radio area, there is a considerably high risk of ultra-low frequency oscillation in the power grid.

![Fig.4. Influence analysis of variation of $K_D$](image)

Based on the above analysis, it can be speculated that the configuration of PID parameters has a great space to enhance the damping level of the system in controlling the damping level of ultra-low frequency band.

### 3. Research on Parameter Adaptive Strategy of Speed Regulating System

#### 3.1 Damping Characteristics of Hydroelectric Speed Regulation System

The most commonly used speed regulating system for hydropower unit at present is the PID microcomputer speed regulator. The speed regulating system of hydropower unit can be simplified and expressed as the structure in Fig.5. In general, the PID parameters are measured on the spot. When it is in the actual operation process of the unit, a set of PID parameters will be adopted if the variation of operation mode is small.

![Fig.5. Basic structure of speed regulating system of hydropower unit](image)

In Fig.5 the transfer function of the speed regulating system of the hydropower unit is as follows.

$$
G_K(s) = \frac{\left[(1+T_D s)K_p + s^2 K_D + (1 + T_D s)K_i\right]}{(s + B_p K_i)(1 + T_D s)}
$$

$$
\times \frac{1}{(1 + T_D s)} \times \frac{1 - T_P s}{(1 + 0.5 T_P s)}
$$

In the light of the algorithm of damping torque of the speed regulation system of prime mover, $s = j\omega$ is substituted to calculate damping torque of the speed regulation system of prime mover:
where $K_1$, $K_2$, $K_3$ and $K_4$ have the following expressions:

$$K_1 = -0.5T_w^2K_D$$  \hspace{1cm} (4)

$$K_2 = (-0.5T_w^2 - 0.5T_w^2T_o B_p K_I - 1.5T_w T_o)K_p$$
$$+ (T_o + 0.5T_w^2 B_p K_I + 1.5T_w T_o B_p K_I + 1.5T_w)K_D$$
$$+ 0.5T_w^2 T_o K_I$$  \hspace{1cm} (5)

$$K_3 = (1 + T_o B_p K_I + 1.5T_w B_p K_I)K_p - B_p K_I K_D$$
$$- (T_o + 0.5T_w^2 B_p K_I + 1.5T_w T_o B_p K_I + 1.5T_w)K_I$$
$$K_4 = B_p K_I^2$$  \hspace{1cm} (6)

Using high differential gain or transient gain will induce excessive oscillation and instability when the connection between generators and interconnected system is considerably strong. Consequently, differential gain is usually set to zero. The regulation time constant of PID governor is generally set at 0.01, which can be neglected when analyzing the damping torque of power system with the PI parameters of governor; in addition, ignoring the influence of permanent slip rate, and then $K_1$~$K_4$ can be simplified, hence the damping torque of the prime motor speed regulating system will be:

$$T_D = \frac{K_p \omega^2 + K}{(1 + T_o^2 \omega^2)(1 + 0.25T_w^2 \omega^2)}$$  \hspace{1cm} (3)

Demarcation frequency $\omega_d$ is the oscillation frequency of the system when the damping torque is 0, which can be represented as:

$$\omega_d = \frac{K_p - (T_o + 1.5T_w)K_I}{(0.5T_w^2 + 1.5T_w T_o)K_p - 0.5T_w^2 T_o K_I}$$  \hspace{1cm} (9)

The formula (5) displays that the oscillation frequency of ultra-low frequency oscillation is mainly affected by the PID control parameters of the speed regulating system, the water hammer effect time constant and the servo system time constant. Among them the PID control parameters are the main adjustable parameters. If the self-adaptive PID control can be adopted, then the speed regulation system of hydropower unit can be controlled in the range of positive damping by setting control parameters, which can enhance the primary frequency regulation capability while reducing the risk of oscillation in the ultra-low frequency band.

According to the demarcation frequency, the influence of the PID control parameters of speed regulating system on the damping can be described as Fig.6. When the parameters of a large power grid system are configured, $K_D$ is often made to equal to 0 in order to avoid the power grid disturbance caused by the differential parameter $K_D$. In view of the situation above, to avoid the complexity of parameter analysis and to reflect the influence of each parameter directly, differential parameter analysis is not introduced in the following parameter analysis.

The distribution of the ratio of PI control parameters in Fig.6 can be divided into the different properties of the damping provided by the speed regulating system and the influence direction of the
parameter variation on the damping. The red shaded part is the area where the hydropower speed regulating system provides positive damping under the demarcation frequency division.

![Figure 6](image-url)

**Fig. 6. Influence of PI controller parameters on damping torque of system at the demarcation frequency.**

### 3.2 Self-adaptive PID parameter optimization method for governor

As described in section 2.1, the setting of PID parameters at different oscillation frequencies will determine whether the governing system provides positive or negative damping. In the present section, the PID parameters are optimized. Since the requirements of primary frequency regulation vary under different disturbances, it is preferable to ensure the rapidity of the system regulation when the speed deviation is small, and the stability of the system regulation are emphasized under larger deviation. Therefore, the improved particle swarm optimization algorithm is used to optimize the PID parameters under different speed deviations with different emphasis on objective functions. Additionally, the optimization results are smoothed so that the PID parameters are linear and continuous when the speed deviation is continuously changed. Under such circumstances, the optimal PID parameters can be obtained under different speed deviations, and the adaptive change of the PID parameters of the governor can be realized to obtain a better frequency regulation effect. The steps are as listed below:

1. Modeling and setting up simulation system parameters. Initial population size $sizpop=50$, maximum number of iterations $MAXgen=100$, the optimization algorithm runs 30 times.
2. Initialize population location and velocity.
3. Set different objective functions through the range of speed deviations.

Traditional particle swarm optimization algorithm only uses the IAE or ITAE index of speed deviation as an objective function. The present study presents an objective function which considers both the rapidity and stability of primary frequency regulation to reflect the ability of primary frequency regulation.

Firstly, two constraint curves are introduced as the constraint conditions of the primary frequency regulation rising time, setting time and steady-state error interval of the control variable $K=[K_P, K_I, K_D]$ of the speed regulating system, so that the primary frequency regulation adjustment time of the system is controlled within 25 seconds and the overshoot is within $\pm 5\%$:

$$-e^{-0.11t} - 0.05 \leq x_i(t) \leq e^{-0.11t} + 0.05$$  \hspace{1cm} (10)

Define an objective function that reflects the primary frequency regulation rapidity of the governor:

$$J_f(K) = C_1 \max \{x_i(t), -e^{-at} - 0.05\}$$

$$+ C_2 \min \{x_i(t), e^{-at} + 0.05\}$$  \hspace{1cm} (11)

Where $a$, $C_1$, $C_2$ are the adjustment coefficients in the objective function. $C_1=C_2=1$ are selected when the system constraint conditions are satisfied. According to the analysis of the influence of the PID parameters on the damping torque, the oscillation frequency of the system under negative damping is close to the demarcation frequency, and the damping level of the regulating system can be approximately
calculated by the formula (3), which reflects the stability level of the speed regulating system under the control variable \( K = [K_p, K_i, K_d] \).

An objective function using absolute error integral criterion IAE is adopted to reflect the stability level index of the system:

\[
J_s(K) = \int_0^{100} |x(t) - \omega_{ref}| \, dt
\]  

(12)

The overall objective function of the system is then obtained:

\[
J(K) = c_1 J_s(K) + c_2 J_2(K)
\]  

(13)

Where \( c_1 \) and \( c_2 \) are non-negative constants. Adjust the weights of the primary frequency regulation performance index and the system stability level index, the optimal control variable \( K = [K_p, K_i, K_d] \) of the speed regulating system at the stage can then be acquired when the overall objective function is minimal. In the process of optimizing the control parameters in the light of the objective function, the influence law of PI controller parameters on the damping torque of the system at the demarcation frequency is referenced.

In the primary frequency regulation under small speed deviation, the rapidity of the system is guaranteed first, and the weights of \( \alpha \) and \( c_1 \), which reflect the performance index of the primary frequency regulation, are ameliorated. Regarding the weights of \( c_2 \), which reflected the stability level index of the system, are increased under a large speed deviation.

(4) Select the objective function depending on the actual speed deviation, and then calculate the particle fitness; the own optimal value \( p_{best} \) and the global optimal value \( g_{best} \) are recorded.

(5) Particles update their velocity and position through individual and population extremes.

\[
V_{p_d}^{k+1} = \omega V_{p_d}^k + a_1 r_1 (B_{p_d}^k - X_{p_d}^k) + a_2 r_2 (B_{p_d}^k - X_{p_d}^k)
\]  

(14)

\[
X_{id}^{k+1} = X_{id}^k + V_{id}^{k+1}
\]  

(15)

In the above formula, \( X_{p_d}^{k+1}, X_{p_d}^k, V_{p_d}^{k+1}, V_{p_d}^k \) represent the positions and velocities of the particles at the \( k+1 \) times and \( k \) times optimizations respectively; \( B_{p_d}^k, B_{p_d}^k \) refer to their own and global optimal value at the \( k \) times optimizations respectively, while \( \omega, a_1, a_2 \) indicate the relative weights.

(6) Determine whether the set run time of the algorithm is reached, and stop when it arrives; otherwise re-determine the speed deviation for the next optimization.

(7) Three sets of PID parameters under different fixed values are obtained by optimization; they are then smoothed so that the speed regulating system can follow the continuous change of the speed deviation to adjust the PID parameters.

3.3 Simulation analysis and results of the 2-zone 4-machine system

For the purpose of verifying the actual effect of the parameter optimization results of the above speed regulating system after smoothing operation, a four-machine and two-zone simulation model based on PSASP is established, in which the 4 units are all hydroelectric units. The speed regulating system adopts PSASP7’s type 8 PID governor, and uses the same PID parameters.

![Fig.7. 2-zone 4-machine system](image)

In the user-defined model of PSASP 7, the PID self-adaptive parameter control logic is added for the opening mode of type 8 governor, and the electrical schematic diagram of governor is illustrated in Fig.8.
When configuring the self-adaptive PID parameters of the governor, a single group of optimized PID parameters, called self-adaptive PID parameter group 1, is initially screened under distinct frequency difference disturbances based on the above improved particle swarm optimization algorithm. On this basis, several groups of PID parameters are smoothed. Corresponding control model in speed regulating system is established, depending on the actual working condition, the PID parameters can be changed continuously and automatically, and the primary frequency regulation control of the hydroelectric governor can be optimized.

**Table 1. Self-adaptive PID parameter group 1**

| ω variation range | K_p | K_i | K_d |
|-------------------|-----|-----|-----|
| 0.0008-0.002      | 9   | 3   | 0   |
| 0.002-0.005       | 6   | 4   | 2   |
| greater than 0.005| 5   | 1   | 1   |

In order to compare the frequency response of different adaptive methods to the system disturbance after the power gap, a control group is set up according to the experience: a comparison analysis is adopted between the self-adaptive parameter group 2 with large parameters under small deviation and the self-adaptive parameter group 3 with high integral parameters under large deviation. Fault settings are as follows: T=1s, generating unit 1 reduces power by 50% and system power disturbance is 150MW.

Fig.9 is the variation curve of the rotating speed of generating unit 2 with different parameter groups. From the view of rotation speed deviation of generating unit 2, when the adaptive parameter group 2 with large parameters under small deviation is adopted, which is similar to that condition under fixed PID parameters, the larger setting value of primary frequency regulation will excite the ultra-low frequency oscillation of the system under high hydropower ratio.

**Fig.9. Curve of rotating speed of generating unit 2**

**4. Conclusion**

In the present study, the influence of the stability of the hydroelectric speed regulating system under high hydropower ratio on primary frequency regulation is studied in detail. A control method of improving primary frequency regulation capability by using self-adaptive PID parameters in the speed
regulation side of hydropower unit is proposed. Firstly, the model of hydropower unit regulation system with PID governor is built, and the specific algorithm of PID parameter optimization of the speed regulating system and the corresponding objective function are put forward.

(1) Improper PID parameters of the speed regulating system may induce the damping characteristics of the system to be negative damping.

(2) A self-adaptive PID parameter control method combined with improved particle swarm optimization algorithm is proposed, which makes the speed regulating system more flexible to participate in the primary frequency regulation process. Under distinct frequency differences, different PID parameters are adopted to make the regulation process of hydropower units more controllable.

(3) The self-adaptive parameters are configured and applied in the multi-machine system. Additionally, based on the actual data of Tibet power grid, and through simulation analysis of typical fault disturbance, it is proved that the primary frequency regulation capability of power grid can be ameliorated by adopting self-adaptive PID parameter governor control.

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