Research on Governor Parameter Optimization to Suppress Ultra-Low Frequency Oscillation of Power System Caused by Hydropower Unit

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Abstract. In the actual power system with hydropower, long-time and ultra-low frequency oscillation events occur many times. It is found that the unreasonable setting of governor parameters is an important reason for the oscillation. Firstly, the single machine on load system model is used to analyse the relationship between the PID parameters of the governor and the system stability, then the relationship between oscillation mode and PID parameters of governor is analyzed by eigenvalue analysis method, and the negative damping provided by speed regulation system is analyzed by damping torque method, and then the particle swarm optimization algorithm is used to optimize the PID parameters. Through the analysis of the step response of the single machine system before and after the optimization and the damping torque coefficient provided by the speed regulation system, it shows the effectiveness of the optimization algorithm. Finally, in the simulation platform MATLAB/SIMULINK, a single machine load system model which is closer to the actual power grid is built. The governor parameters of the generator are simulated and verified, and the PID parameters are adjusted by using the parameters obtained by the optimization algorithm. The results show that the optimized parameters have a good suppression for the ultra-low frequency oscillation.

1. Introduction
On March 8, 2016, Yunnan power grid implemented asynchronous networking mode. The AC tie line between Yunnan power grid and the main network of China Southern Power Grid was disconnected, and only three DC lines, Chu Sui, Pu Qiao and Niu Cong, were connected to the main network and sent power. During the test, an ultra-low frequency oscillation (ULFO) with an oscillation period of about 20 s (oscillation frequency of about 0.05 Hz) and a frequency fluctuation range of 49.9 ~ 50.1 Hz occurred in Yunnan power grid. The oscillation lasted about 25 min. after exiting the primary frequency regulation performance of some power plants, the oscillation stopped. It is found that the control parameters of hydraulic turbine governor and the negative damping effect caused by water hammer effect are the main causes of ultra-low frequency oscillation. By optimizing the PID parameters of hydraulic turbine governor, the ultra-low frequency oscillation can be effectively suppressed [1-7].

According to previous studies, many methods to solve the phenomenon of ultra-low frequency oscillation have been proposed. Ref. [8] puts forward the PI governor tuning standard of Pumped Storage Hydropower Station, which can provide frequency support capability in an independent power system with a large amount of renewable energy. According to the analysis of [2] the ULFO of Yunnan power grid is a non electromechanical oscillation mode. Optimizing the governor parameters can effectively improve the stability of the system. Ref. [9] uses correlation coefficient index to screen ultra-low
frequency mode sensitive generators in multi machine system, and applies particle swarm optimization algorithm to adjust PID parameters. Ref. [10] gives the time domain solution of the guide vane opening response and the response time formula of the widely used governor model. The value set method is used to analyze large-scale power systems and adjust controller parameters in [11]. In [12], the PI parameters of the governor are optimized to improve the damping torque. Authors in [13] suggest that PFR should be withdrawn and negative damping should be used as an emergency strategy.

By establishing the transmission model of single machine single load system, this paper analyzes the simplified governor and complex governor respectively, and then optimizes the PID parameters in the single machine single load model of complex governor through PSO optimization algorithm to obtain the optimal PID parameter solution. Finally, the asynchronous 4-machine 2-area system is simulated and analyzed in MATLAB/SIMULINK to verify the influence of PID parameter setting on ultra-low frequency oscillation of power system.

2. Analysis model of ULFO in power system
This part introduces the analysis method of ultra-low frequency oscillation and the mathematical model of each module in the actual power system.

2.1. Hydroturbine and Governor Model
In the simplified turbine model adopted in this paper, we consider ignoring the elasticity of the diversion pipeline, and the flow only produces rigid water hammer. Its transfer function is:

$$G_m(s) = \frac{\Delta P_m}{\Delta \mu} = \frac{1-T_w s}{1+0.5T_w s}$$

(1)

In this formula, changing with the load, which is between 0.5s and 4s at full load, is the turbine inertia time constant.

The function of the governor of the hydropower unit is to control the opening of the guide vane of the hydraulic turbine. The controller of the parallel PID governor is often used, and the transfer function is as follows:

$$G_{\text{gov},h}(s) = \frac{\Delta \mu(s)}{-\Delta \phi(s)} = \frac{K_p s^2 + K_i s + K_d}{B_p K_i + s} \frac{1}{1 + T_y s}$$

(2)

In this formula, $\Delta \mu$ is the turbine guide vane opening deviation; $K_p$, $K_i$, $K_d$ are the proportional, integral and differential parameters of the governor; $B_p$ is the adjustment coefficient; $T_y$ is the time constant of the servo system.

2.2. Steam turbine and Governor Model
Steam turbine is a power mechanical device that converts the kinetic energy of high temperature and high pressure steam into rotating mechanical energy. In this paper, the simplified model of steam turbine is adopted. This type of steam turbine considers the volume effect of both high-pressure steam and intermediate reheat steam, and its transfer function is as follows:

$$G_{\text{t},s}(s) = \frac{\Delta P_t}{\Delta \phi} = \frac{1+s F_{\text{t} \text{m}} T_{\text{t} \text{m}}}{(1+s T_{\text{t} \text{in}})(1+s T_{\text{t} \text{re}})}$$

(3)

In this formula, $\Delta \phi$ is the disturbance value of control valve; $F_{\text{t} \text{m}}$ is the proportion of the power generated by the medium and high pressure cylinder steam in the total power of the turbine; $T_{\text{t} \text{in}}$ is the time constant of reheating the steam turbine; $T_{\text{t} \text{in}}$ is the main intake volume and the time constant of the steam chamber.

The governor model of steam turbine mainly includes mechanical hydraulic system and DEH system based on microprocessor. The transfer function of typical steam turbine regulator system adopted in this paper is as follows:
&^g (1) \gamma_{G}\tau_{T} = \omega_{\Delta} + R(1 + sT_{g})} 

Where, \( R \) is the differential adjustment coefficient of the governor and \( T_{g} \) is the response time constant of the governor.

2.3. Generator model
The generator model used in this paper adopts the three-phase synchronous motor modeled in D and Q coordinate system in Simulink component library.

2.4. Excitation system model
The excitation system model used in this paper adopts IEEE 1 synchronous motor voltage regulator combined exciter in Simulink component library.

3. Influence of speed regulation system parameters on ULFO
This part introduces the model used to study the mechanism of ultra-low frequency oscillation. Then the relationship between PID parameters and ultra-low frequency oscillation is analyzed by eigenvalue analysis method and damping torque method. It provides a theoretical basis for the next part to study the PID parameter optimization and tuning of speed regulation system.

3.1. Single machine on load transfer function model
In this paper, a single machine on load system which can accurately reflect the system frequency change and active power fluctuation is adopted, which is often built based on Phillips-Heffron model. On the basis of this model, adding the prime mover governor module, the single machine on load transfer function model can be obtained.

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\[ \omega_{\text{ref}} \sum_{\text{Governor}} \Delta P_{\text{r}} \rightarrow \Delta \omega \]

Figure 1. Transfer function block diagram of single machine system.

The transfer function of single machine single load primary frequency modulation closed-loop system can be obtained as follows:

\[ T(s) = \frac{(K_{p} s^2 + K_{p} s + K_{i})(1 - T_{w} s)}{(B_{p} K_{i} + s)(1 + T_{i} s)(1 + 0.5 T_{w} s)(T_{i} s + D s) + (K_{p} s^2 + K_{p} s + K_{i})(1 - T_{w} s)} \] (5)

3.2. Eigenvalue analysis
According to the system transfer function, the characteristic root of the system can be solved, and then the oscillation mode corresponding to each characteristic root can be determined. By using the eigenvalue, it can be found that the oscillation angular frequency of the system when the critical oscillation process occurs is \( \omega \)

\[ \omega = \sqrt{(1 + T_{i} B_{p} K_{i})D + B_{p} K_{i}(0.5 T_{w} D + T_{i}) - (K_{i} T_{w} - K_{p})} \]

\[ 0.5 T_{w} D + T_{i} + (0.5 + 0.5 T_{i} B_{p} K_{i})T_{w} - K_{i} T_{w} \] (6)
It can be found that the critical oscillation frequency of the system increases gradually with the increase of the proportional value of the proportional parameter and the integral parameter. When the ratio is too small, the critical oscillation frequency of the system is less than 0.1Hz. At this time, the oscillation process of the system is classified as ultra-low frequency oscillation.

3.3. Analysis of damping torque method

According to the damping torque method, the damping ratio of the system is:

$$\zeta = \frac{K_{rd} + K_{L} + D}{2\sqrt{K_{rd}a_0}}$$

(7)

Through the above derivation process, it is explained from the basic mechanism that the speed regulation system will provide negative damping to the system. It provides a theoretical and guiding basis for the adjustment of speed regulation system parameters.

4. PID parameter optimization method based on PSO

This paper presents a comprehensive optimization objective considering both the dynamic performance of speed regulation system and the ability to suppress ultra-low frequency oscillation. The particle swarm is randomly distributed in space, and the fitness value is calculated according to the initial position of each particle. Each particle takes its current position as the individual optimal position, and the position of the particle with the best fitness value as the global optimal position. Then, the next position of all particles is updated by using the position and velocity update formula, and the fitness values of all particles are calculated again. Comparing the fitness values calculated twice, each particle updates the individual optimal position, and after updating the individual optimal positions of all particles, the particle position with the best fitness value is the global optimal position again. Repeat the above process of updating the individual optimal position and the global optimal position until the position convergence of all particles meets the accuracy requirements or the number of iterations exceeds the limit.

5. Simulation analysis of load system of single hydro motor unit

In this part, the load model of single hydro motor unit is built successively in MATLAB/SIMULINK simulation platform, and the simulation verification is carried out. In the simulation model, the hydropower unit supplies power to loads 1, 2, 3 and 4 through 40km transmission line. From right to left, loads 1 and 2 are 20MW and load 3 is 15MW. The capacity of the generator is set to 117.65mw, the inertia coefficient is set to 3.658s, and the frequency of the system is 50Hz. Setting the PID parameter of the governor of the hydropower unit to $K_p = 1.4, K_i = 0.8, K_d = 0.5$, and observe the frequency change curve of the system after simulation, as shown in Figure 2. It can be seen that the system has an ultra-low frequency oscillation with an oscillation period of 20s, which is in the form of equal amplitude oscillation, and the system is unstable.

According to the optimization result, adjust the PID parameter to $K_p = 3.8838, K_i = 0.35799, K_d = 1$, and the frequency change curve of the generator after simulation is shown in Figure 3. It can be seen that the ultra-low frequency oscillation can be effectively suppressed after optimizing the PID parameters of the speed regulation system. The above simulation in the model comprehensively verifies the effectiveness of the proposed speed regulation system parameter optimization method to suppress ultra-low frequency oscillation.
6. Conclusion
Through eigenvalue method and damping torque method, the influence process of PID parameters of hydraulic turbine governing system on ultra-low frequency oscillation is analyzed, and the PID parameter setting scheme is determined. Through the comprehensive objective optimization scheme, the PID parameters of the governor are optimized, the overall damping value of the system is improved, and then the ultra-low frequency oscillation of the system is suppressed. The governing system models of hydraulic turbine and steam turbine are analyzed, the ultra-low frequency oscillation analysis model of power system is established, and the model is simulated to verify the effectiveness of the proposed ultra-low frequency oscillation suppression method.
References

[1] Y. Chen, Y. Zhao, G. Geng, Q. Jiang, W. Liu and L. Li. Suppression Strategy of Ultra-Low Frequency Oscillation in Yunnan Power Grid with BESS [C]. 2019 North American Power Symposium (NAPS), Oct. 2019, Wichita.

[2] G. Tao-Rong, W. Guan-Hong and L. Tao. Analysis and control on ultra low frequency oscillation at seeding end of UHVDC power system [C]. 2014 International Conference on Power System Technology, Oct. 2014, Chengdu.

[3] Y. Chen et al. Analysis of ultra-low frequency oscillation in yunnan asynchronous sending system [C]. 2017 IEEE Power & Energy Society General Meeting, Jul. 2017, Chicago.

[4] L. Cheng, W. Wang, G. Xu, F. Dou, X. Wu and J. Cheng. Damping Analysis and Parameter Adjustment of Hydraulic Turbine Governor under Ultra-low Frequency Oscillation [C]. 2019 IEEE 3rd Conference on Energy Internet and Energy System Integration (EI2), Nov. 2019, Changsha.

[5] Q. Liu, C. Li, Y. Chen and R. Yang. Damping Torque Analysis of the Influence of Different Types of Dead Band on Ultra-low Frequency Oscillation [C]. 2019 IEEE 8th International Conference on Advanced Power System Automation and Protection (APAP), Oct. 2019, Xi’an.

[6] C. Zheng et al. Analysis and control to the ultra-low frequency oscillation in southwest power grid of China: A case study [C]. 2018 Chinese Control And Decision Conference (CCDC), Jul. 2018, Shenyang.

[7] R. Yang et al. Influence of dead band of turbine governors on ultra-low-frequency oscillation in Hydro-Dominant power system [C]. 8th Renewable Power Generation Conference (RPG 2019), Oct. 2019, Shanghai.

[8] Martínez-Lucas G, Sarasúa JI, Sánchez-Fernández JÁ, Wilhelmi JR. Frequency control support of a wind-solar isolated system by a hydropower plant with longtail-race tunnel [J]. Renew Energy. 2016, 90(05):362–76.

[9] G. Chen et al. Optimization Strategy of Hydrogovernors for Eliminating Ultralow-Frequency Oscillations in Hydrodominant Power Systems [J]. IEEE Journal of Emerging and Selected Topics in Power Electronics. 2018, 6(09):086-109.

[10] Yang W, Yang J, Guo W, Norrlund P. Response time for primary frequency control of hydroelectric generating unit [J]. Int J Electr Power Energy Syst. 2016, 74(01):16–24.

[11] J. Zhou et al. Large-Scale Power System Robust Stability Analysis Based on Value Set Approach [J]. IEEE Transactions on Power Systems. 2017, 32(09):4012–4023.

[12] Chongxi Jiang , et al. Ultra-low frequency oscillation analysis and robust fixed order control design [J]. International Journal of Electrical Power & Energy Systems. 2019, 104(07):269-278.

[13] Lei Chen , et al. Online emergency control to suppress frequency oscillations based on damping evaluation using dissipation energy flow [J]. International Journal of Electrical Power & Energy Systems. 2018, 103(06):414-420.