Research on parameter optimization of damping controller based on fuzzy control algorithm

Yamin Fang*, Jinyang Huang
Jining Polytechnic, Jining, Shandong, 272103, China.

ABSTRACT

The system response caused by large power disturbance includes large deviation of generator rotor angle. Its stability depends on the initial operating conditions and the severity of disturbance. Fuzzy control is an attractive new control method and technology in the control field. This paper mainly takes PSS(power system stabilizer) as the research object to study the method of parameter optimization of damping controller. Fuzzy control algorithm is used to optimize and improve the control parameters of PID control algorithm, which makes the optimized PID algorithm more suitable for vibration control of PSS. Its core idea is to use fuzzy control algorithm to optimize and update the control parameters of PID algorithm in real time, overcome the limitations of PID control algorithm, and make it suitable for PSS vibration control. The simulation results show that the power system's ability to suppress low-frequency oscillation is significantly enhanced by adopting PID controller optimized by fuzzy control algorithm.

Keywords: Fuzzy control; Damping controller; PID control.

1. INTRODUCTION

With the continuous development of power system, the interconnection of provincial power grids realizes the optimal allocation of resources in different regions, which enhances the economy and reliability of the system. On the other hand, it makes the dynamic behavior of the power system more complicated, and puts forward higher and higher requirements for the stable operation of the system [1-2]. In order to suppress the low-frequency oscillation caused by negative damping, installing PSS(power system stabilizer) is a simple and practical method. Stabilization is actually a dynamic process, which mainly refers to the process of readjusting the voltage phase angle of the synchronous motor caused by the disturbance of the power system, resulting in the imbalance between the output and load of the system. After a series of dynamic changes, a new running state is established. The system response caused by large power disturbance includes large deviation of generator rotor angle. Its stability depends on the initial operating conditions and the severity of disturbance [3].

There are many methods to analyze the small disturbance stability of power system. According to their mathematical models, these methods can be divided into three types: time domain simulation method, eigenvalue analysis method and frequency domain method [4-5]. In the actual power system, because the system state matrix is asymmetric, although it is highly sparse, there is no effective eigenvalue calculation method using this sparsity at present [6-7]. PSS is an additional excitation control, whose essence is to provide an additional signal to the excitation system, and to increase the damping torque of the generator through the excitation system [8]. Cheng Qiming et al. revealed the relationship between the real-time electricity price of load and the related Lagrange multiplier [9]. Sutianyu et al. revealed that the dual variable of the interior point method contains a lot of economic information [10]. Zou Hongbo et al. analyzed the constraints of generator rotation reserve in electricity market environment in detail [11].

*Corresponding author email: jnjdxfym@163.com

Seventh International Conference on Mechatronics and Intelligent Robotics (ICMIR 2023), edited by Srikanta Patnaik, Tao Shen, Proc. of SPIE Vol. 12779, 127792W · 0277-786X · doi: 10.1117/12.2689774

Power system is a typical complex system, and its accurate mathematical model is difficult to establish. Fuzzy control is an eye-catching new control method and technology in today's control field. By summarizing the experience and requirements of experts into a number of rules and adopting simple, fast and flexible means, it can achieve the automation and intelligence goals that are difficult to achieve with classical and modern control, so it is more and more widely used in many fields [12]. In this paper, PSS is the research object, and the method of parameter optimization of damping controller is studied. Fuzzy control algorithm is used to optimize and improve the control parameters of PID control algorithm, which makes the optimized PID algorithm more suitable for vibration control of PSS.

2. RESEARCH METHOD

2.1 Objective function of optimization problem

Reactive power optimization is based on the fixed active power output of the system power supply, taking the reactive power output of the power supply and the position of the transformer tap as control variables, and the objective function is the optimal power flow with the minimum active power loss of the system. Active power flow takes the output of active power source as the control variable, and the objective function is the optimal power flow with the lowest total fuel cost of the system. Reactive power optimization can not only improve system voltage quality, but also reduce network loss and save energy. The mathematical model of reactive power optimization is mainly composed of three parts: objective function, equality constraints and inequality constraints. Generally speaking, the small disturbance stability analysis is mainly concerned with the position of the conjugate eigenvalue of the system on the complex plane.

The conjugate eigenvalue is also called oscillation mode, and its position on the complex plane not only determines the small signal stability of the system, but also determines the quality of the dynamic response of the system. It can be said that the process of parameter optimization of damping controller is a process of system damping redistribution, and it is necessary to make overall consideration, so as to ensure that no new weak damping eigenvalues will be generated in the process of strengthening the weak damping electromechanical oscillation mode eigenvalues.

The function of excitation regulator is to process and amplify the input control signals, so as to generate appropriate excitation control signals. Excitation regulator usually includes amplification link, excitation system stabilization link and amplitude limitation link. An effective solution is to adopt the tracking center trajectory method. In the process of optimization, the relaxation variable and Lagrange multiplier only need to meet the condition of being greater than or less than zero, instead of requiring the iteration point to be in the feasible region, which can simplify the calculation process. The purpose of optimizing the damping controller is to improve the control performance of the damping controller in the power system, to output effective reactance value, to provide optimal damping for various oscillation modes, and to restore the power system to the stable operation point after the fault as quickly as possible. Based on this objective, the objective function of damping controller optimization is proposed as follows:

Typical generator oscillation mode system:

$$J = \int_{t_0}^{t_f} \tilde{\omega}_t^2 dt \tag{1}$$

Where t_f, t_0 represents the start time and end time of simulation calculation respectively, and $\tilde{\omega}_t$ represents the speed variable of each generator in the inertial center coordinate.

Considering the small disturbance stability of the system, the inequality constraint of the dynamic characteristics of the reactive power system should be added in the reactive power optimization. The objective function of the dynamic characteristics of the reactive power system can be merged into the objective function of the reactive power optimization, and the system can be optimized according to the idea of multi-objective optimization.

There are many ways to combine the small signal stability index with the system line loss index to construct the objective function. It is intuitive to use the weight coefficient to sum them up, and adjusting the weight coefficient can also flexibly change the optimization direction. Therefore, the objective function of reactive power optimization considering the small signal stability of the system is:

$$\min F = \omega_1 F_R + \omega_2 F_D \tag{2}$$

$$F_R = \frac{F_Q}{F_Q^0} \tag{3}$$

Where F_Q^0 is the value before reactive power optimization ω_1, ω_2 is the weight coefficient of system network loss and small disturbance stability optimization respectively. In the optimization process, every time the above objective function value is obtained, the control parameters are adjusted to calculate the power flow distribution of the system, then F_R is obtained from the power flow distribution, and finally F_D is obtained by eigenvalue analysis. The optimization goal is to minimize the sum of the two.

This objective function is a mathematical transformation, which transforms the state variable representing the kinetic energy of the system, that is, the square trajectory of the generator angular velocity, into a scalar function of the damping controller parameters, to evaluate the damping effect of the system, and to find a group of damping controller parameters that make the system trajectory decay fastest through optimization algorithm.

2.2 Parameter optimization of damping controller

Because the weak connection between regional power grids weakens the damping of the system, low-frequency oscillation may be one of the main problems that restrict the mutual power support between regional power grids in the initial stage of national power grid operation. Flexible AC transmission system is relative to conventional AC transmission system. Generally, the operation parameters of conventional AC transmission system can't be adjusted and controlled. When the operation mode of the system changes or is disturbed, it is difficult for the transmission system to automatically adjust to this change. PSS is used to add auxiliary signals to the excitation system to enhance the damping of the generator, which can effectively suppress the electromechanical oscillation of the system. After the PSS parameters of the system are set, they will not be changed for a relatively long period of time, while the system often performs economic dispatch, and the operation mode of the system will change greatly in a relatively short period.

The most important unconstrained optimization method is gradient method, which includes steepest descent method, Newton method, conjugate gradient method and quasi-Newton method. Among them, conjugate gradient method is the most suitable method, which has the advantages of simple algorithm and small storage requirement. Conjugate gradient method is between steepest descent method and Newton method. It overcomes the sawtooth phenomenon of the steepest descent method, thus improving the convergence speed. Its iterative formula is relatively simple, and it is unnecessary to calculate the second derivative of the objective function. Compared with Newton's method, it reduces the amount of calculation and storage, and it is an effective optimization method.

PID control algorithm takes the error between the output value and the expected value of the system as the input signal, and linearly combines the proportion P, integral I and differential D of the error to obtain the structural control quantity and complete the control of the structure. The schematic diagram of PID control is shown in Figure 1, and the calculation formula can be expressed as:

$$u = K_P e + K_I \int e dt + K_D \frac{de}{dt} \tag{4}$$

Where: u is the control quantity; e is the error between the controlled quantity and the target value; K_P, K_I, K_D is a proportional, integral and differential parameter.

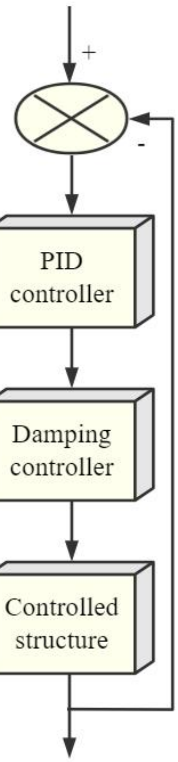

Figure 1. Structure block diagram of PID control system

As the earliest improved and applied control algorithm, PID control algorithm still plays a role in many fields. However, PID control develops slowly in the vibration control of building structures. PID control algorithm itself is relatively simple, and it regulates the specified input of the system in proportion, integration and differentiation. Such a single input mode makes PID control algorithm have obvious advantages over the vibration control of simple structures. For example, when tracking the robot's motion trajectory, PID algorithm determines the amount of deflection according to the offset of the robot's motion trajectory.

In this paper, a fuzzy control optimization PID control algorithm is proposed. Its core idea is to use fuzzy control algorithm to optimize and update the control parameters of PID algorithm in real time, overcome the limitations of PID control algorithm, and make it suitable for PSS vibration control.

Fuzzy reasoning is the core of fuzzy control, and its essence is the establishment of fuzzy rules. Choosing a reasonable transformation method can give full play to the decision-making role of fuzzy reasoning and improve the control effect. The coefficient weighted average method is to reflect the "participation degree" of each fuzzy quantity through the coefficient, so as to calculate the output. Its mathematical expression is:

$$u = \sum k_i \cdot x_i / \sum k_i \tag{5}$$

Where, u is the output value after ambiguity resolution, x_i is the i th input ambiguity, and k_i is the weighting coefficient corresponding to x_i, which will affect the characteristics of the control system and needs to be determined according to the actual situation.

In order to ensure the comprehensive optimization of fuzzy rules, membership function parameters and quantization factors, a hybrid coding strategy combining real-valued coding with non-real-valued coding is proposed, that is, membership function parameters and quantization factors are coded with real-valued coding and fuzzy rules are coded with non-real-valued coding. Aiming at the non-real value coding representing fuzzy rules, the strategy of updating its meme is proposed as follows:

$$X_{PW}^{k+1}(j)=\begin{cases} X_{\inf}^{k}(j), & Y(j)=1 \\ X_{PW}^{k+1}(j), & Y(j)=0 \end{cases} \quad j=1,2,\cdots,p_l \tag{6}$$

Where X_{PW} represents the part of meme in the worst solution X_W of the secondary meme complex that represents fuzzy rules; $X_{\inf}$ represents the part of meme that represents fuzzy rules in the optimal solution X_B of the secondary meme complex or the global optimal solution X_G ; Y is a randomly generated binary sequence; The coding length of $X_{PW}, X_{\inf}, Y$ is all equal to p_l .

In the process of fuzzification and defuzzification, the input variables should be transformed from the basic universe to the corresponding universe of fuzzy sets, and the fuzzy output universe should be transformed into the corresponding output variables. In this process, the input variables should be respectively multiplied by the corresponding displacement quantization factor and speed quantization factor, and the output variables should be multiplied by the voltage scale factor. After calculation, the best control effect can be achieved when the quantization factor is selected according to the following formula.

$$\begin{aligned} &k\_dis = 1/D_{\max} \\ &k\_vel = 1/V_{\max} \\ &k\_volt = -1000 \end{aligned} \tag{7}$$

Where k_dis, k_vel, k_volt is the displacement quantization factor, the velocity quantization factor and the voltage scale factor, and $D_{\max}, V_{\max}$ is the maximum value of the absolute value of displacement and the maximum value of the absolute value of velocity in the uncontrolled state.

The flow chart of fuzzy control optimization PID algorithm is shown in Figure 2. The input is the error between displacement and limit value, and the output is the input current of PSS.

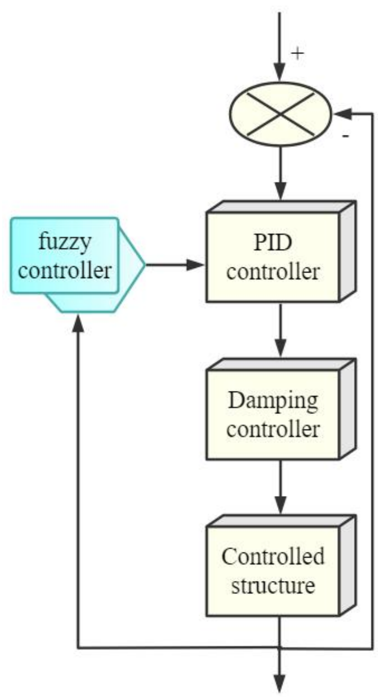

Figure 2. Flow chart of fuzzy control optimization PID algorithm

3. EXAMPLE ANALYSIS

The effectiveness and robustness of the proposed method will be illustrated by two test systems. In the example system, all generators adopt biaxial model, and the load adopts constant impedance model. Generally, one typical operation mode, two N-1 operation modes, or three typical operation modes are selected when PSS parameters are adjusted, and then PSS parameters are optimized on this basis, and finally the set PSS parameters are verified by the selected operation modes. Using the system parameters optimized by active power as the initial value to set PSS parameters, and checking in various operation modes can improve PSS adaptability as much as possible.

The improved PID algorithm is used to optimize PSS parameters, and the population in the model is set to 50 individuals. After PSS parameters are optimized, the characteristic values of electromechanical oscillation modes of the system after active power flow optimization are shown in Table 1 below.

Table 1. Characteristic value of electromechanical oscillation mode of power flow optimized system

Mode 1		**Mode 2**		**Mode 3**	
Eigenvalue	Damping ratio	Eigenvalue	Damping ratio	Eigenvalue	Damping ratio
-1.2628±j13.7594	0.2964	-2.3748±j14.251	0.1537	4.6424±j11.409	0.1019
-2.146±j14.8131	0.173	-4.108±j15.1009	0.1478	2.2715±j14.175	0.101
-4.4451±j15.829	0.2983	-1.192±j17.3491	0.1577	2.1256±j15.7126	0.1185
-3.6757±j17.044	0.1731	-4.3003±j18.4637	0.1692	4.815±j17.519	0.1215
-5.948±j20.1377	0.2984	-3.1847±j21.6695	0.1544	1.3293±j18.833	0.2042

It can be seen from the table that after the active power flow optimization, the minimum damping ratio of the electromechanical oscillation mode of the system under the three operation modes is greater than 0.1, that is, PSS can provide appropriate damping for the system under various electromechanical oscillation modes.

Figure 3 shows the convergence performance of the improved PID algorithm in the case of the third objective function. For comparison, the convergence performance of the conventional PID algorithm is also shown in the figure. It can be seen that the improved PID algorithm has a good search efficiency in each value of control parameters, while the conventional PID algorithm has a particularly low search efficiency when the control parameters are small.

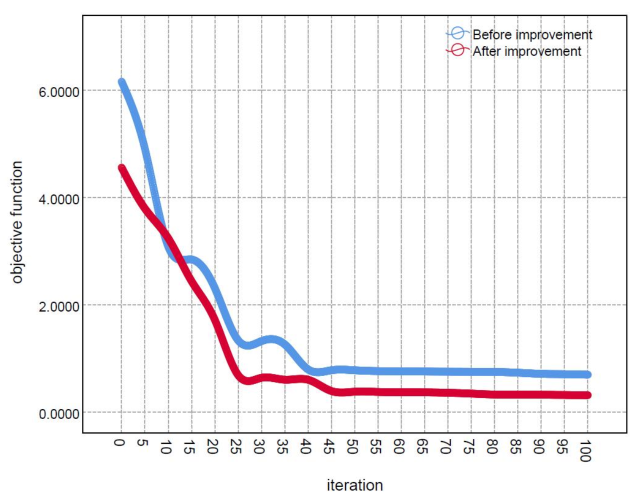

Figure 3. Comparison of convergence performance of algorithms

Fig. 4 shows the rotor angle simulation curve of PID control with fuzzy control optimization when the fault removal time is 0.25s when the single-phase grounding is short-circuited. The rotor angle simulation curve of PID control (scheme 1) and PID control optimized by fuzzy control (scheme 2) is put into use when the system has low frequency oscillation.

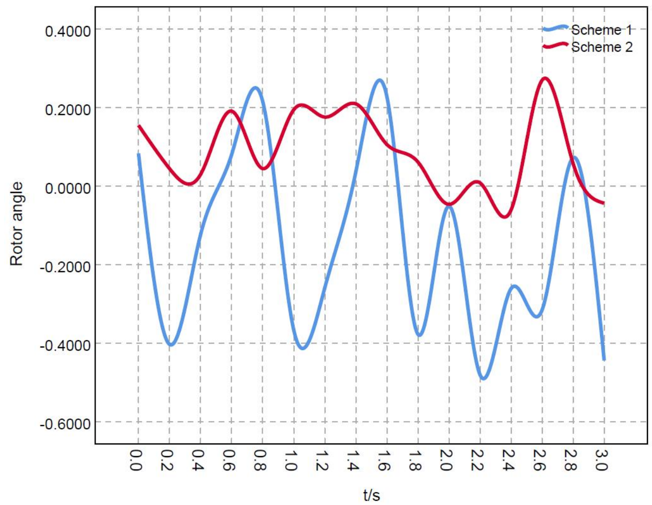

Figure 4. Simulation curve of rotor angle in short circuit

It can be seen that the power system's ability to suppress low-frequency oscillation is obviously enhanced by adopting PID controller optimized by fuzzy control algorithm.

4. CONCLUSION

In order to suppress the low-frequency oscillation caused by negative damping, installing PSS is a simple and practical method. Stabilization is actually a dynamic process, which mainly refers to the process of readjusting the voltage phase angle of the synchronous motor caused by the disturbance of the power system, resulting in the imbalance between the output and the load of the system. After a series of dynamic changes, a new running state is established. In this paper, the parameter optimization of damping controller based on fuzzy control algorithm is studied. Fuzzy control algorithm is used to optimize and improve the control parameters of PID control algorithm, which makes the optimized PID algorithm more suitable for vibration control of PSS. The simulation results show that the power system's ability to suppress low-frequency oscillation is significantly enhanced by adopting the PID controller optimized by fuzzy control algorithm.

REFERENCES

[1] Wang, C., Li, X. Y., Parameter coordination optimization strategy of pss and statcom damping controller based on ifa. Power System and its acta automatica sinica, 29(9): 9-13+20 (2017).

[2] Lv, F., Zhang, J., Parameter Optimization Design of svc Additional Damping Controller Based on pso. Power Capacitor and Reactive Power Compensation, 37(2), pp. 6 (2016).

[3] Zhu, X. L., Zhang, Y. M., Li, X. Y., Liu, T. Q., Guo, L., Zhang, L. K., Optimal design based on flexible DC low-frequency oscillation damping controller. Hydropower Energy Science, 34(11), pp. 4 (2016).

[4] Zhou, J. H., Che, Y. B., Shu, Z., Hu, X. Q., Coordinated optimization design of pss and svc damping controller based on chaos mutation particle swarm optimization algorithm. advanced technology of electrical engineering and energy, 37(5), pp. 7 (2018).

[5] Wang, Y., Yang, H. L., Xiao, X. Y., Zhou, B., Shi, P., Wang, H. F., Analysis and optimization design of suppression method of additional subsynchronous damping controller for doubly-fed fan. Electric Automation Equipment, 2022(008), pp. 042 (2022).

[6] Xu, Y., Wang, X. T., Bai, S., Jie, D., Optimal Design of Subsynchronous Damping Controller for hvdc Transmission System of Direct Drive Wind Farm. Southern Power Grid Technology, 12(004), pp. 24-30, (2018).
[7] Ai, S. B., Tang, X., Wang, H. Y., Optimal design of additional damping controller and control parameters for photovoltaic power plants. Journal of Electric Power Science and Technology, 2020(006), pp. 035 (2022).
[8] Zhou, Q. W., Zhang, G. M., Time-delay stability control simulation of industrial process observers. Computer Simulation, 35(11), pp. 228-231 (2018).
[9] Cheng, Q. M., Tan, F. R., Cheng, Y. M., Gao, J., Zhang, Y., Research on control method of dfig grid-side converter based on internal model observer and passive controller under unbalanced power grid. High Voltage Technology, 043(010), pp. 3280-3289 (2017).
[10] Su, T. Y., Du, W. J., Wang, H. F., Reduced-order design method of subsynchronous damping controller for parallel wind farms with multiple direct-drive permanent magnet synchronous generators. Journal of Electrical Technology, 34(1), pp. 12 (2019).
[11] Zou, H. B., Chai, T., Bao, G., Optimal design of sssc damping controller based on improved bbo algorithm. Power Grid and Clean Energy, 36(9), pp. 7 (2020).
[12] Zhang, J. C., Zhang, T. T., Xiong, H. T., Han, B., Su, C. F., Parameter tuning method and field application of reactive damping controller in flexible excitation system. Journal of Electrical Technology, 2022 (017), pp. 037 (2022).