Coordinated Optimization of Multi Control System for Steam Turbine Generator Unit

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ABSTRACT

A method of the coordinated optimization of multi control system for steam turbine generator unit was proposed in this paper. The primary frequency modulation performance and dynamic stability of the power system were taken into account in the method. The multi-control system to be optimized includes the excitation regulation system, the power system stabilizer (PSS), the speed control system and the boiler-turbine coordinated control system (CCS). And the taboo search (TS) algorithm was introduced as a means to obtain the optimal values of the system control parameters. The simulation result shows that the method can coordinate the primary frequency modulation performance and the dynamic stability of the system, and can effectively prevent the low frequency oscillation caused by the improper multi control system parameters setting.

Keywords: Speed control system, boiler-turbine coordinated control system, taboo search.

INTRODUCTION

The traditional research on the dynamic stability of power system mainly focuses on the effect of excitation control parameters on system damping. It has been shown that when the magnification of the excitation regulator is too large, the system damping becomes weaker, and a small disturbance of the system may lead to amplitude oscillation [1]-[3]. In order to solve this problem, the power system stabilizer (PSS) is designed to provide positive damping to the power system to improve the dynamic stability of the system [4].

With the widely use of large capacity units in the modern power systems and the increasing of the grid peak valley load difference of power grids, large units need strong primary frequency modulation capability, in order to meet the load requirements and frequency stability of power grids. However, with the popularity of digital electro-hydraulic
(DEH) control system, the response speed of governor is greatly improved, which has more significant effects on the dynamic stability of the system. Therefore, adjusting the parameters of DEH control system can improve the performance of primary frequency control, and may cause low frequency oscillation in power system [5]-[7]. In the automatic control operation of the steam turbine generator unit, the reference value and the rate of change of load, which are the inputs of the governor control, are the output signals of the boiler-turbine coordinated control system (CCS) [8]. So the control parameters of CCS will also affect the performance of primary frequency modulation and dynamic stability of the system.

A coordinated optimization of multi control system for steam turbine generator unit was presented in this paper. The parameter tuning of the excitation regulator or PSS has been studied, based on some intelligent optimization algorithms, such as the genetic algorithm (GA), the particle swarm optimization (PSO), the ant colony (ACO) algorithm and so on [9]-[15]. However, the optimization in this paper was extended to multi control system, including the excitation regulation system, the power system stabilizer (PSS), the speed control system and the boiler-turbine coordinated control system (CCS). Through the comprehensive consideration of the primary frequency modulation performance and dynamic stability of the system, the parameter optimization of the unit multi control system was realized by means of taboo search (TS) algorithm, a kind of intelligent and global optimization algorithm.

ESTABLISHING THE SYSTEM MODEL

Steam Turbine Model

In that overall buckling behavior can be ignored in stub columns, local geometric imperfection was added into the models by using the lowest buckling mode shape obtained in the first step of analysis as mentioned before. The local imperfection amplitude, h/200 and the material model suggested by Joanna [16] were used in the finite element analysis.

In the actual operation, the turbine is a three-cylinder system. The time constants of the low pressure cylinder and the medium cylinder are too large to take their dynamic response into account. So the steam turbine model can be simplified as a link that only considers the volume constant of the high-pressure cylinder. The simplified transfer function is given by

$$G(s) = \frac{F_{hp}}{1 + sT_{ch}}$$

(1)

Where T_{ch} is the inlet chamber time constant and F_{hp} is the high-pressure cylinder power coefficient.

Governor Model

Currently the most widely used electro-hydraulic control system controller is digital electro-hydraulic controller. In the process of building the model, the electro-hydraulic converter can be ignored because it is fast. The linear displacement sensor is generally set to unit negative feedback, and the PID control links only retain the proportion and integral links. The simplified transfer function is given by

$$G(s) = \frac{K_p}{1 + sT_s} \frac{1}{1 + sT_s}$$

(2)

Where TS is the time constant of oil motive; KP, TR are respectively the proportion of PID controller and integral time constant.
Excitation System Model

In the excitation regulation system, the generator terminal voltage signal, a feedback signal, is converted to the control signal for the system to provide electromagnetic torque, through the integral, differential and proportional control links, as shown in Figure 1.

Where $Te$ is the excitation response time constant, the proportional control parameter $KA$ is the excitation adjustment magnification.

Power System Stabilizer (PSS) Model

The Power System Stabilizer (PSS) provides positive damping for the system by introducing feedback signals into the system. The equivalent rotor angular velocity signal is converted to the output signal of PSS, through the signal gain, signal filtering, phase compensation and amplitude limiting links, as show in Figure 2.

Where $K_{STAB}$ is the power system stabilizer gain; $T_W$ is the time constant; $T_1$ and $T_2$ are the phase compensation time constants; $V_{smax}$ and $V_{smin}$ are respectively the upper limit and lower limit of input signal amplitude.

CCS Load Instruction Management System Model

To meet the unit load capacity and operational safety, the load instruction of CCS is formed from three aspects, i.e. the load instruction of automatic dispatch system (ADS), the unit set load instruction and the power grid frequency modulation required load instruction. The switch $T_1$ selects the ADS load instruction or the unit set load instruction as the target load command. The switch $T_2$ selects the input or cut of the primary frequency modulation. The function generator $f_1(x)$ defines the frequency modulation dead band and frequency modulation characteristic.
As shown in Figure 3, the control parameters of this model include the switch $T_1$, the switch $T_2$, and the frequency modulation dead band and characteristics of $f_1(x)$. CCS Main Steam Turbine Control System Model and CCS Main Boiler Control System Model

Figure 4 shows the coordinated control mode. The power deviation signal is the input of the proportional integral power regulator PID1, the output of which is the load reference value into the DEH. To prevent large fluctuations of the main steam pressure, the main steam pressure deviation signal is introduced into the regulator PID1 via the function $f_3(x)$, and the function $f_3(x)$ defines the main steam pressure regulation characteristic. Therefore, the control parameters of the steam turbine main control system include the proportional frequency $K_{P1}$, integral multiplication $K_{I1}$, and differential link multiplication $K_{D1}$, and the frequency modulation dead band and characteristics of $f_3(x)$.

The main steam pressure deviation signal is the input of the proportional integral regulator PI2, and the output command of the regulator acts on the boiler sub-control system. The boiler main control also increases the dynamic adjustment of the power deviation, where the unit power deviation signal is introduced into the input of the regulator PI2 via the function $f_2(x)$. Therefore, the control parameters of the boiler main control system include the proportional multiplication $K_{P21}$, integral multiplication $K_{I2}$, and the frequency modulation dead band and characteristics of $f_2(x)$.

OPTIMIZATION OBJECTIVE FUNCTION

Index of Primary Frequency Modulation Performance

The primary frequency modulation performance is measured by

$$d = \frac{\sum_{i=1}^{N} |P_{x,i} - P_{u,i}|}{N}$$

(3)
Where \( P_e \) is the actual frequency modulation required power; \( P_0 \) is the frequency modulation load instruction; \( N \) is the total sampling times. In order to measure the primary frequency modulation performance of the steam turbine, error tracking is carried out for the actual frequency modulation of the initial response phase and the intermediate transition phase. Therefore, the total sampling time is 50 seconds.

**Index of Dynamic Stability Performance**

The eigenvalues of the state matrices can be obtained from the characteristic equation of the system. Each pair of conjugate complex eigenvalues \( \sigma \pm j \omega \) corresponds to an oscillation mode of the system, and the damping ratio can be obtained by

\[
\xi = \frac{\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{4}
\]

The index of dynamic stability performance is the damping ratio of the system.

**Optimization Objective Function**

\[
F = w_1d + \frac{w_2}{\xi} + q \frac{w_3}{\xi} \tag{5}
\]

In the equation (5), \( w_1 \) and \( w_2 \) are the weights of primary frequency modulation performance index and dynamic stability performance index respectively, and the weight changes with the sampling period. When the sampling period is 0.1 seconds, the value range of \( w_2/w_3 \) is \( 40 \sim 80 \). A penalty function is introduced in the optimization objective function, and \( q \) is the penalty factor. When damping ratio is negative, the value of \( q \) is -100.

**INTELLIGENT OPTIMIZATION ALGORITHM**

Taboo search (TS) algorithm, a kind of global iterative optimization algorithm, can avoid roundabout search through the introduction of taboo rule and can release some better point from the taboo table based on aspiration criterion, thus ensuring the ultimate realization of global optimization. The concepts of objective function, neighborhood, taboo rule, and aspiration criterion and termination rule are the key of TS.

**Concepts of TS**

**CONCEPT OF NEIGHBORHOOD**

The number of all control parameters involved in optimization is \( n \), so the current point \( x \) is an \( n \)-dimensional vector. The point \( x \) can be represented as \( x=[x_1, x_2, \ldots, x_n] \), so the upper limit is \( x_u=[x_{u1}, x_{u2}, \ldots, x_{un}] \) and the lower limit is \( x_l=[x_{l1}, x_{l2}, \ldots, x_{ln}] \). In order to establish the neighborhood of the current point \( x \) in the \( n \)-dimensional space, the neighborhood space is divided by concentric hyper-rectangles shown as follows.

\[
H_i(x, h_{i-1}, h_i) = \left\{ x \mid \begin{array}{l}
h_{i-1,j} \leq \left| x_j - x_j^* \right| < h_{i,j}, \\
x_{u,j} < x_j^* < x_{l,j}, \quad j = 1, 2, \ldots, n
\end{array} \right\} \tag{6}
\]
\[
H_0(x, h_0) = \left\{ x \mid \begin{align*}
\|x_j - x_l\| &< h_{0,j}, \\
x_{u_j} &< x < x_{l_j}, \quad j = 1, 2, \ldots, n
\end{align*} \right\}
\]

\[h_i = 2 \times h_{i-1}, i = 1, 2, \ldots, k\]

In the above equations, \(h_0\) is an independent variable and \(x_j\) is the \(j\)th component of the current point \(x\). Take a point randomly in each of the \(k\) concentric hyper-rectangles (except \(H_0\) to avoid the algorithm falling into the loop.), and then the \(k\) points together constitute the neighborhood of the current point \(x\).

CONCEPT OF OBJECTIVE FUNCTION

In the iterative search process, the objective function of TS is the optimization objective function.

CONCEPT OF TABOO RULE

Taboo objects are the current point and its surrounding neighborhood \(H_0\), and the current point and its objective function value will be placed in the taboo table. When the taboo table is full, the first objects to be placed in the taboo table would be set free in order to put in new objects.

CONCEPT OF ASPIRATION CRITERION

Compare the objective function \(f(x)\) of the point \(x\) with \(f(x_{\text{best}})\) of the current optimal point \(x_{\text{best}}\). And if \(f(x) < f(x_{\text{best}})\), point \(x\) satisfies the aspiration rule.

CONCEPT OF TERMINATION RULE

The iteration is terminated when the optimal solution is not improved within a certain number \((L)\) of iterations, or when the maximum number \((M)\) of iterations is reached.

Process of TS

![Figure 5. Process of Taboo Search Algorithm.](image)
Figure 5 shows the process of taboo search algorithm.

Step 1: Determine the range of values for each control system parameter and initialize the current point \( x = x_0 \), the optimal point \( x_{best} = x_0 \), so the optimal objective function value \( f(x_{best}) = f(x_0) \). Empty the taboo table.

Step 2: Calculate the objective function value of each point in the neighborhood of the current point.

Step 3: Select the point \( x^* \) of the smallest objective function value in the neighborhood.

Step 4: Determine if \( x^* \) satisfies the aspiration criterion. If satisfied, update the current point to \( x_{best} = x^* \), \( f(x_{best}) = f(x^*) \) and go to step 6; If not, go to step 5.

Step 5: Determine if \( x^* \) satisfies the taboo rule. If satisfied, the \( x^* \) is deleted from the neighborhood and returns to step 3; if not, the current point is updated to \( x^* \) and go to step 6.

Step 6: Update taboo table. If the termination rule is satisfied, terminate the calculation; if not satisfied, then return to step 2.

**SIMULATION RESULT**

A two-machine infinite system was established in the simulation software. The rated power of the generator is 330MW, of which the excitation system is self-shunt excitation and the model of the PSS is PSS2A. The control mode of CCS is the coordinated control mode based on the turbine following. The load instruction of CCS is formed from the unit set load instruction and the power grid frequency modulation required load instruction.

The following control parameters were selected as the parameters to be optimized: excitation regulator \( K_{A} \), PSS gain \( K_{STAB} \), the proportion magnification of the main steam turbine control of CCS \( K_{P1} \), the proportion magnification of the main boiler control of CCS \( K_{P2} \), the proportion magnification of the governor \( K_{P} \).

**Initialization**

The current point \( x = [K_A, K_{STAB}, K_{P1}, K_{P2}, K_{P}] \) was initialized according to the classic value of the control parameters. The initial point \( x_0 = [200, 6, 1, 1, 1] \); the upper limit \( x_u = [800, 30, 2, 2, 5] \); the lower limit \( x_l = [50, 0, 0, 0, 1] \).

**Setting of TS Parameters**

The neighborhood of the current point was divided into 5 concentric hyper-rectangles, and the radius of the center rectangle was set as \( h_0 = 0.01 \times (x_u - x_l) \).

The taboo table length was 5, and set the iterations number as \( L = 80 \), \( M = 2000 \).

**Result**

According to the six steps of the TS algorithm, the optimized parameters were searched iteratively and finally the global optimal point was obtained as \( x_{best} = [500, 8, 1.5, 1.5, 4] \). Figure 6 shows the actual frequency modulation response curve of the system under initial control parameters. Figure 7 shows the actual frequency modulation response curve of the system under optimal control parameters.

Comparing the two curves shown in Figure 6 and Figure 7, it can be seen that the primary frequency modulation performance and the dynamic stability of the optimized system has been improved.
CONCLUSION

A method of the coordinated optimization of multi control system for steam turbine generator units has been presented in this paper. According to the simulation result, this method can realize the coordinated optimization of the primary frequency modulation performance and the dynamic stability of the system, and effectively prevent the low frequency oscillation caused by improper parameters setting of multi control system.

REFERENCES


