Parameter Optimization of Coordinated Control System Based on Intelligent Algorithm

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Abstract. This paper studies the issue of modeling and control of large unit coordinated control systems. The system is regarded as a three-input and three-output control object. Based on this, the system model is decoupled and the controller is designed. The controller is designed using an intelligent PID method, which based on genetic algorithm and fuzzy control model. The proposed method can optimize the control effect while ensuring the basic requirements, in order to achieve the goal of improving the dynamic process quality and improving the combustion efficiency.

1. Introduction

At present, China’s primary energy is mainly coal, and coal for power generation accounts for more than half of the total coal consumption [1]. Reducing energy consumption is the focus of high-efficiency energy-saving power generation in the thermal power industry. Therefore, the basis for ensuring the safe of the unit and the coordination of the control system are related to the automation level of the thermal power unit, which ultimately affects the efficiency and energy consumption level of the power generation.

In the modeling of the furnace system, as early as 1965, Adams et al. studied the mechanism modeling of the DC boiler [2]. Since then, scholars at home and abroad have intensive study on the modeling of the coordinated control system, using various mechanisms and experiments. The modeling method successfully established a variety of coordinated control system models. Literature [3-6] introduced the methods of modeling and parameter identification based on different principles. The system model has also evolved from a simple two-input and two-output control object to a more complex and accurate three-input three-output control object. Meanwhile, the PID control method for model controller design is gradually maturing, and a variety of different intelligent algorithms are applied to the thermal power industry: Li et al. used a genetic algorithm to build a model for the generator set, and verified the availability of the model through simulation [7]; Jiao introduced a PID method based genetic algorithm to optimize PID parameters in thermal power system of thermal power unit [8]; Chang improved genetic algorithm to optimize the coordination control parameters [9]; Zhang compared the application of fuzzy control based control strategy with traditional control strategy in coordinated control system [10] and proved that fuzzy control has the function of improving control quality.

In this paper, a three-input and three-output model which is suitable for engineering application is established for the modeling and control of the coordinated control system. The decoupling method
ensured that each control channel is independent of each other. On this basis, the intelligent PID algorithm based on genetic algorithm and fuzzy control is applied to optimize control parameters and improve the control quality.

2. The decouple of coordinated control system

Coordinated control system is a key component of large unit. Its function is mainly to make the unit respond to the load requirements of the grid when the external load command changes, and balance the energy supply and demand relationship between the steam turbine and the boiler, and maintain the main parameters of the unit within the allowable range to ensure the safety and economics of the unit. As a control object of the coordinated control system, the steam turbine-boiler is a nonlinear, strongly coupled three-input three-output system. The change of steam inlet valve, fuel quantity and water supply volume of the steam turbine will directly lead to changes in the output power of the system, the enthalpy of the separator outlet, and the pressure before the machine. The coordinated control system is regarded as the control object of three inputs and three outputs, and a feature model suitable for engineering implementation is established. Among them, the parameters of the coordinated control system model are obtained by the parameter identification method based on genetic algorithm. The control object inputs are respectively expressed as: turbine valve opening degree $\mu_T$, fuel amount $B$, and water supply flow rate $W$; the control object output is: unit output power $N$, pre-machine pressure $P$, separator outlet enthalpy (temperature) $H$. For ultra-supercritical units, the model can be simplified as appropriate when the unit is operating near rated conditions, depending on the temperature effect of the turbine valve opening and the effect of feed water flow on the unit's output power:

$$
\begin{bmatrix}
N \\
P \\
H
\end{bmatrix} = 
\begin{bmatrix}
G_{11} & G_{12} & \mu_T \\
G_{21} & G_{22} & B \\
G_{31} & G_{32} & W
\end{bmatrix}
\begin{bmatrix}
\mu_T \\
B \\
W
\end{bmatrix} 
$$

(1)

$$
G_{11}(s) = \frac{157.6942s}{(8.8999s + 1)(45.8783s + 1)}
$$

(2)

$$
G_{12} = \frac{3.1904}{(94.4774s + 1)(22.7701s + 1)(128.0847s + 1)}
$$

(3)

$$
G_{21} = \frac{-42.2122}{(105.3025s + 1)(87.7958s + 1)}
$$

(4)

$$
G_{22}(s) = \frac{0.3027}{(8.2968s + 1)(101.5385s + 1)}
$$

(5)

$$
G_{23} = \frac{10.5315s}{(75.0311s + 1)(41.2927s + 1)(105.7540s + 1)}
$$

(6)

$$
G_{32} = \frac{1.9382}{(145.7527s + 1)(30.4466s + 1)(75.3121s + 1)}
$$

(7)

$$
G_{33} = \frac{-4.9925}{(10.8201s + 1)(16.5258s + 1)(2.2987s + 1)}
$$

(8)

In order to facilitate the next controller design, this paper uses a feed forward decoupling method to process the model matrix since the model has strong coupling and large lag. The control system is decoupled from a complex system with a high degree of coupling into three single-input single-output control systems with independent control channels.

The class feed forward decoupling network function relationship diagram is as follows:
After calculation, the decoupling matrix is:

$$
D = \begin{bmatrix}
D_{11}(s) & D_{12}(s) & D_{13}(s) \\
D_{21}(s) & D_{22}(s) & D_{23}(s) \\
D_{31}(s) & D_{32}(s) & D_{33}(s)
\end{bmatrix}
$$

Which

$$
D_{11}(s) = D_{22}(s) = D_{33}(s) = 1 \\
D_{13}(s) = D_{31}(s) = 0
$$

$$
D_{12}(s) = \frac{-0.0202(8.8999s + 1)(45.8783s + 1)}{s(94.4774s + 1)(22.7701s + 1)(128.0847s + 1)}
$$

$$
D_{21}(s) = \frac{139.4523(8.2968s + 1)(101.5385s + 1)}{(105.3025s + 1)(87.7958s + 1)}
$$

$$
D_{23}(s) = \frac{-34.7919s(8.2968s + 1)(101.5385s + 1)}{(75.0311s + 1)(41.2927s + 1)(105.7540s + 1)}
$$

$$
D_{32}(s) = \frac{0.3882(10.8201s + 1)(16.5258s + 1)(2.2987s + 1)}{(145.7527s + 1)(30.4466s + 1)(75.3121s + 1)}
$$

Through class feed forward decoupling, the structure of the coordinated control system is simplified and remains unchanged. On this basis, the design of the controller is to design the controller for the transfer function $G_{11}(s), G_{22}(s), G_{33}(s)$, in which the values of the Eqs. (2), (5), and (8) are respectively taken:

$$
G^* = \begin{bmatrix}
G_{11}(s) & 0 & 0 \\
0 & G_{22}(s) & 0 \\
0 & 0 & G_{33}(s)
\end{bmatrix}
$$

For verifying whether the three channels of the coordinated control system after decoupling are independent of each other, step signals are added to the three channels separately in the Simulink simulation block diagram. The simulation duration is 200 seconds, and the output results of the three channels in three cases are observed. The blue curve represents the output of channel one (turbine valve opening $\mu_f$ - unit output power $N$), the green curve represents the output of channel two (fuel amount $B$ - machine front pressure $P$), and the red curve represents channel three (water supply flow $W$ - The output of the separator exit threshold $H$):
3. The PID algorithm design based on intelligent algorithm

PID controller has the advantages of simple control law, stable operation, high robustness and strong adaptability. However, in the large unit coordinated control system, although the traditional PID controller only three parameters need to be set, and the setting is still a very difficult problem. This is because not only the expected response results are obtained when tuning the parameters, but also many complex limitations of PID control are required. Therefore, the method of using genetic algorithm, fuzzy control, immune regulation, neural network and other means to optimize parameters is developed.

3.1. PID parameter tuning based on genetic algorithm

The genetic algorithm has the advantages of less computation time, parallelism and simple operation process, and is suitable for a coordinated control system with large computational complexity and real-time performance. Therefore, this paper selects the PID parameter tuning based on genetic algorithm to optimize the controller parameters for the $\mu_T$-N channel and W-H channel of the coordinated control system.

The basis of genetic algorithm is Darwin's theory of natural selection, which develops on this basis, and therefore contains three aspects of the theory of natural selection: inheritance, variation, survival struggle and survival of the fittest [12]. Its basic operations are: copying, crossing, and mutation. These three processes can select individuals with stronger ability from the original population and generate new individuals, and at the same time, can obtain better solutions with better optimization results in a larger space.

The specific steps for tuning PID parameters based on genetic algorithm are:

1. Determining decision variables and constraints
The parameters set in this paper are the three parameters of proportional, integral and differential of PID. Initially setting the PID parameters of the control channel uses the Z-N method. The approximate value range is determined as the constraint condition.

(2) Establish optimization model

For obtaining a dynamic characteristic of the transition process that satisfies the requirements, the coordinated control system has better control effect. In this paper, the absolute value of the systematic error is integrated, and the index is selected as the parameter, and the minimum objective function is selected by using it. At the same time, the function also includes the square term of the input limit, so as to avoid the influence of too much control. Based on the above considerations, this paper finally selects the formula based on the formula introduced in the reference as the optimal index function [14], the formula is as follows:

\[ J = \int_{0}^{\infty} \left( w_1 |e(t)| + w_2 u(t)^2 + w_3 t_u \right) dt \]

In the above formula, \( e(t) \) represents the systematic error, \( u(t) \) represents the output, \( w_1, w_2, w_3 \) represent different weight values, respectively.

At the same time, the formula has a penalty function to deal with overshoot and avoid the effects of overshoot.

(3) Determine the encoding and decoding methods.

Considering the convenience of genetic manipulation, this paper adopts binary coding. In Matlab, the three parameters P, I and D are encoded to form a string, which forms the original population. After decoding, the optimal solution can be obtained.

(4) Determine the individual evaluation method.

The genetic algorithm is based on the fitness function in its operation, and basically does not refer to other external information. Therefore, it is very important to select an individual fitness function that meets the actual needs when writing the algorithm, which will affect the final search results. The general process of evaluating individual fitness is: first, the individual encoded string is decoded to obtain the individual's phenotype; secondly, the corresponding individual's objective function value is calculated according to different phenotypes [8]; the optimization requirement of this problem is to calculate the corresponding individual's fitness value according to the established conversion principle.

(5) Determine the operating parameters of the genetic algorithm.

The population size (Size), genetic algebra G, and crossover probability Pc are determined according to different target requirements. According to many times running the program and debugging on the Matlab platform, this paper takes Size=30, G=100, Pc=0.9. According to the PID parameter obtained by the Z-N method, the parameter range of the control channel is determined: for channel one (turbine valve opening degree \( \mu_T \) - unit output power N), the value range of \( K_p \) is [1, 10], and the value range of \( K_i \) is [1, 2], the value range of \( K_d \) is [0,1]; for channel three (feed water flow W-separator exit threshold H), the value range of \( K_p \) is [-10,0], the value range of \( K_i \) is [-0.1,0], and the value range of \( K_d \) is [-0.1,0].

(6) Determine genetic algorithm program.

The genetic algorithm program was written by Matlab, and the optimization values of the three parameters were obtained. The tuning parameters result is: Channel 1 (turbine valve opening - unit output power N).

\[ K_p = 6.8989, \quad K_i = 1.0000, \quad K_d = 0.8004, \quad J = 9.0100 \]
3.2. **PID parameter tuning based on fuzzy control**

Fuzzy control is robust and has advantages in solving problems in process control such as strong coupling, time-varying, and large lag. Coordinated control system P-B channel has the characteristics of large lag, so this paper adopts the PID parameter tuning method optimization parameter based on fuzzy control.

Compared to traditional logic systems, it is closer to human thinking and natural language. Fuzzy control first writes the experience of an expert or a staff member as a fuzzy rule, and then blurs the real-time signal output by the sensor. The processed signal is sent as an input to the rule judgment, the reasoning is performed in the inference engine, and finally the result of the inference output is sent to the actuator.

The basic steps for designing a fuzzy controller are as follows:

In this paper, the structure is the controller with error \( e \) and error change \( ec \) as input, \( \Delta K_p, \Delta K_i, \Delta K_d \) as output.

After the fuzzy control structure is determined, the input and output fuzzy sets of the controller are defined. The input and output fuzzy sets used in this paper are as follows:

Input: the two inputs are error \( e \) and error change \( ec \). The scope of its change is defined as:

\( e, ec = \{-3, -2, -1, 0, 1, 2, 3\} \)

Its fuzzy subset is \( e, ec = \{NB, NM, NS, ZO, PS, PM, PB\} \).

After determining the input and output fuzzy sets, you need to define the membership function. Constructing an appropriate membership function is the basis for the fuzzy control operation to obtain optimized results. The "reference function" method is adopted to construct the membership function. The classical trigonometric membership function and the bell-type membership function are selected as the membership functions of input and output respectively, and the relevant parameters of the
membership function are determined. The PID parameter setting must take into account the interaction of the three parameters of proportional, integral and differential with time and the relationship between them. The following table shows the fuzzy control table for each of the three parameters:

| $\Delta K_p / \Delta K_i / \Delta K_d$ | $e(t)$ | NB | NM | NS | ZO | PS | PM | PB |
|---------------------------------------|-------|----|----|----|----|----|----|----|
| **e(t)**                              |       |    |    |    |    |    |    |    |
| NB                                   |       |    |    |    |    |    |    |    |
| $\Delta K_p$                         |       |    |    |    |    |    |    |    |
| PB/NB/P                              |       |    |    |    |    |    |    |    |
| S                                     |       |    |    |    |    |    |    |    |
| NM                                   |       |    |    |    |    |    |    |    |
| $\Delta K_i$                         |       |    |    |    |    |    |    |    |
| PB/NB/N                              |       |    |    |    |    |    |    |    |
| S                                     |       |    |    |    |    |    |    |    |
| NS                                   |       |    |    |    |    |    |    |    |
| ZO                                   |       |    |    |    |    |    |    |    |
| $\Delta K_d$                         |       |    |    |    |    |    |    |    |
| PM/NB/NS                             |       |    |    |    |    |    |    |    |
| O                                     |       |    |    |    |    |    |    |    |
| PS                                   |       |    |    |    |    |    |    |    |
| ZO                                   |       |    |    |    |    |    |    |    |
| PM/NB/N                              |       |    |    |    |    |    |    |    |
| S                                     |       |    |    |    |    |    |    |    |
| NS                                   |       |    |    |    |    |    |    |    |
| ZO                                   |       |    |    |    |    |    |    |    |
| PM/NB/PS                             |       |    |    |    |    |    |    |    |
| O                                     |       |    |    |    |    |    |    |    |
| PM/NS/NS                             |       |    |    |    |    |    |    |    |
| O                                     |       |    |    |    |    |    |    |    |
| PM/PB/NS                             |       |    |    |    |    |    |    |    |
| B                                     |       |    |    |    |    |    |    |    |
| PM/ZO/NS                             |       |    |    |    |    |    |    |    |
| B                                     |       |    |    |    |    |    |    |    |
| PM/PB/PS                             |       |    |    |    |    |    |    |    |
| B                                     |       |    |    |    |    |    |    |    |

Anti-fuzzification and fuzzy reasoning are the last links of fuzzy control. Among them, the reasoning function is realized by the inference engine, which is mainly responsible for matching and reasoning, matching the input variables with the established rules and then drawing conclusions according to the corresponding rules. The result of the inference engine is a fuzzy value that cannot be used directly as a result. The defuzzification function converts this result into a clear amount as the final result. In this paper, we try to determine the method of using the area center of gravity as the defuzzification method by trying different methods.

According to the control structure, cybernetic domain and control rules determined in the previous section, a two-input and three-output system is built in Matlab using the fuzzy toolbox to generate a fis file. Design and complete the control block diagram in Simulink, import the programmed program into the fuzzy logic controller, and adjust the quantization factor and scale factor. After debugging, this paper selects the quantization factor $e$, $ec$ as 1, and the scale factor as $\Delta K_p = 5.8$, $\Delta K_i = 0.167$, $\Delta K_d = 0.0005$. The block diagram of Simulink is as follows:
4. Simulation results comparison and analysis.

In the light of the calculation results above, the results of the PID parameter are written into the simulation module, and the simulation sub-module is established to simulate the coordinated control system.

The following are the results of the step response of the three channels using traditional PID parameter tuning and genetic algorithm/fuzzy control PID parameter setting. The simulation time is 200 seconds. Among them, the traditional PID parameter tuning selects the Z-N method setting: the green curve
represents the traditional PID parameter setting output; the blue curve represents the intelligent parameter based PID parameter setting output.

Turbine valve opening degree - unit output power N-channel Z-N method setting result is:
\[ \Delta K_p = 3, \Delta K_i = 1.5, \Delta K_d = 0 \]

Fuel quantity B—machine front pressure P channel Z-N method setting result is:
\[ \Delta K_p = 19.6, \Delta K_i = 0.5, \Delta K_d = 0 \]

The feed water flow W-separator outlet enthalpy H channel Z-N method setting result is:
\[ \Delta K_p = -0.5, \Delta K_i = -0.012, \Delta K_d = 0 \]

Figure 9. \( \mu_T \) — N channel step response simulation renderings

Figure 10. B-P channel second step response simulation effect diagram

Figure 11. W-H channel step response simulation effect diagram

By comparison it can be seen:
For the \( \mu_T \)-N channel with small hysteresis, the overshoot of the result obtained by the traditional PID parameter tuning method (ZN method) is relatively large, reaching 11%, and the adjustment time
is also long, which is 6.349 seconds; and the genetic algorithm PID parameter is used. The setting greatly reduced the overshoot, down to 1.3%, and the adjustment time was also reduced to 2.653 seconds, thus achieving better control results.

For the B-P channel with large hysteresis, the fuzzy control PID parameter tuning not only reduces the overshoot (from 28% using the traditional tuning method to 18%) but also accelerates the response compared to the traditional tuning method (Z-N method), shortening the rise time from 26.6 seconds to 20 seconds.

For the W-H channel, the PID parameter setting of the genetic algorithm extends the rise time from 22.55 seconds to 24.53 seconds in the Z-N method, and the overshoot is reduced by a certain sacrifice in terms of rise time, which is reduced from 25.2% of the Z-N method to 14%. In addition, the number of oscillations is greatly reduced, so the dynamic process of the proposed method is more stable than the traditional Z-N tuning method.

5. Conclusion

In this paper, the modeling and control problem of unit-unit coordinated control system is studied. Firstly, the control object is decoupled from a complex three-input and three-output coupling system into three separate control systems with independent control channels, and then based on genetic algorithm and fuzzy control. The PID parameter setting method performs parameter setting on the controller of the coordinated control system. It can be seen from the comparison with the traditional methods that the response curve after PID parameter tuning using the proposed intelligent algorithm has faster response speed and less oscillation times.

Acknowledgments

This work was supported/sponsored by China Southern Power Grid Corp science and technology project (Contract No.: GDDW2120150301JJ00035).

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