Application of Iterative Feedback Tuning Method in Superheated Steam Temperature Control System

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Abstract: Taking a 600 MW supercritical once-through boiler as the study object, this paper designed an IFT-based two-degree-of-freedom (DOF) PID superheated steam temperature control system. Besides, the IFT-PID controller was formed and compared with the conventional tuning method. The simulation results show that this method can be successfully applied to great-inertia and large-lag controlled objects, with evident superiority.

1.Introduction
In the thermal control of modern thermal power plant, the superheated steam temperature (main stream temperature) at boiler outlet is one of the main boiler parameters and the maximum temperature of working medium in the whole steam-water stroke, playing a significant role in the safe and economical operation of power plant. Therefore, the main steam temperature must be strictly controlled nearby the given value. In general, the temporary deviation and long-term deviation of main steam temperature in medium-pressure and high-pressure boilers is not allowed to exceed $\pm 10^\circ C$ and $\pm 5^\circ C$, respectively. Besides multi-capacity, great inertia and large lag, the main steam temperature object usually shows certain nonlinear and time-varying characteristics. The conventional cascade PID superheated steam temperature control system fails to achieve any satisfying control effect due to the difficulty in parameter tuning.

As a model-free method driven by the system I/O data, iterative feedback tuning (IFT) method was proposed by a Swiss scholar H. Hjalmarsson in 1994[1-2]. IFT can be used to calculate the unbiased gradient (namely, differential unbiased signal output by the system) of indicator function for controller parameters, which is an outstanding contribution made by this method. From the existing studies, the IFT method can be combined to simplify the tuning of controller parameters, avoid model identification, etc. At present, the iterative feedback tuning method has been applied in many industrial fields[3-5], and the effect is good. In consideration of simple algorithm and favorable convergence of IFT, the already established steam temperature object model was combined in this study to introduce the IFT method into the traditional PID controller and constitute an IFT-PID controller. This controller was capable of the self-tuning of PID parameters. By comparing it with the other conventional PID tuning methods, the effectiveness and superiority of the proposed control algorithm were proven.
2. Iterative Feedback Tuning (IFT) Algorithm and Convergence Proof

2.1. Steps of IFT algorithm

Step 1: Implement the closed-loop system experiment for three times after selecting the initial parameters of controller.

Step 2: Calculate \( \tilde{y}(\rho_i) \), \( \text{est} \left[ \frac{\partial y}{\partial \rho}(\rho_i) \right] \), \( u(\rho_i) \) and \( \text{est} \left[ \frac{\partial u}{\partial \rho}(\rho_i) \right] \).

Step 3: Calculate the positive definite matrix \( R_i \).

Step 4: Update the controller parameters according to Equation (1).

\[
\rho_{i+1} = \rho_i - \gamma_i R_i^{-1} \text{est} \left[ \frac{\partial J}{\partial \rho}(\rho_i) \right]
\]  

(1)

Step 5: Test the performance of new controller, if the performance is not satisfied, return to step 1, and use \( i \) to replace \( i+1 \). If the performance requirement is satisfied, end the iteration process[6].

![Algorithm Flowchart of IFT Method](image)

2.2. Convergence proof of IFT method

A two-degree-of-freedom (DOF) system was designed for a controlled object with first-order inertia and pure lag using the IFT method, and the performance of this control system was compared with that of conventional Ziegler-Nichols (Z-N) tuning method and internal model control-IMC method. The
simulation results showed that the IFT method was of better control effect.

The controlled object was \( G(s) = \frac{1}{20s + 1}e^{5s} \), where the pure lag was replaced by third-order Padé approximation. The expected output response was unit step signal, and the design objective of control system was to track expected output with system output. The sampling time was 0.01 s. The two controllers chosen were PI and PID controllers, namely, \( C_r = Kp + Ki \frac{z}{1 - z^{-1}} \) and \( C_y = Kp + Ki \frac{z}{1 - z^{-1}} + Kd(1 - z^{-1}) \). The controller parameter vector to be tuned was \( \rho = [Kp, Ki, Kd] \).

For the IFT method, the initial values of controller parameters have a great bearing on the tuning result, and the local minimum point can be avoided by selecting proper initial controller parameters. It was found through a lot of simulation experiments in this study that under normal circumstances, good updating results of controller parameters could be acquired by taking the controller parameters obtained through the Ziegler-Nichols (ZN) tuning method as the initial parameters in IFT-based tuning. The experimental time of closed-loop system was 70 s each time, and the three closed-loop system experiments totally lasted 210 s during each updating and iteration process of controller parameters.

Table 1 shows the results of controller parameter vector under the three tuning methods. The change curves of controller parameter vector after each iteration are displayed in Figure 2, which will be of certain guiding significance to tuning of controller parameters in engineering practice. Figure 2 (d) shows the change curves of system control index \( J \) in the closed-loop system after each iteration. It could be known that after the gradual iteration, the control index was reduced step by step until reaching a satisfactory control system design index. The step response curves of closed-loop system and control signal curves of the three tuning methods are shown in Figure 3 and Figure 4. Obviously, the tuning time of IFT method was shorter than that of ZN method and IMC method, with an only very small overshoot. This control effect was realized by the control signal output by the controller, namely, the control signal under the IFT method was smaller than those under ZN method and IMC method, as shown in Figure 3. The simulation results manifest that the IFT method is applicable to the control system design of first-order inertial plus pure lag object just as in this example. As aforementioned, the IFT method is not only applicable to the parameter tuning of simply structured controllers like PID controller, but moreover, it can achieve satisfactory tuning effect only if the controller structure is known.

| Tuning method | Kp  | Ki  | Kd  |
|---------------|-----|-----|-----|
| ZN tuning     | 4.05| 0.44| 9.33|
| IMC tuning    | 3.61| 0.17| 7.56|
| IFT tuning    | 2.41| 0.11| 0.89|
Figure 2. Change Curves of Controller Parameters and Control Index in Each Iteration process
(a) Change Curve of PID Parameter $K_p$; (b) Change Curve of PID Parameter $K_d$;
(c) Change Curve of PID Parameter $K_i$; (d) Change Curve of Control Index $J$
3. Simulation Study of Application of IFT Method in Superheated Steam Temperature Control System

In order to prove the effectiveness of IFT method in the thermal object control and its superiority relative to conventional tuning methods, the second-order transfer function model of superheated steam temperature to fuel quantity under 100%-boiler maximum continuous rating (BMCR) was chosen to design and simulate the control system. The design method of this control system was also applicable to superheated steam temperature models with different disturbance degrees under other working conditions, the methods were similar, so no unnecessary details were given.

The IFT method was introduced into the traditional PID controller to form an IFT-PID controller,
which could complete the self-tuning of PID parameters. As a linear controller, PID controller forms a control deviation according to the given value and actual value, realizes a linear combination of proportion, integral and differential of control deviation to form a controlled quantity, and further controls the controlled object. At present, the PID controller plays a dominant role in the industrial production process. In this study, the conventional PID control algorithm processed through the difference transformation (sampling time: \( T = 1s \)) was used as below:

\[
u(k) = Kp + \frac{Ki}{1 - z^{-1}} + Kd(1 - z^{-1}) e(k)
\]

A two-DOF control system was adopted in this study. As shown in Figure 5, \( C_r = C_y = C \), where C is the PID controller. Through the simple equivalent transformation of block diagram, Figure 5 can be transformed into a standard PID control system as shown in Figure 6.

![Figure 5. Block Diagram of Closed-Loop System](image1)

![Figure 6. Diagram of Standard PID Control System](image2)

When \( C_r = C_y = C \), the data of the third closed-loop system experiment was no longer needed, so the experiment just needed to be done twice in each iteration process of controller parameters.

For the controlled object of steam temperature in this study, each closed-loop system experiment lasted 1000 s through multiple simulation experiments due to the great inertia, large lag and long tuning time, and therefore, the closed-loop system experiment was carried out totally for 2000 s in each updating process of controller parameters. The standard input signal \( r \) was selected as unit step signal, \( i \) represented the number of iterations, \( j = 1, 2 \) denoted the number of experimental times, and the experimental rules were as follows and could be expressed by Figure 7.
Thus, the controller parameters remaining to be tuned by iterative feedback included \( \rho = [K_p, K_i, K_d] \), the controller adjusted its own parameters according to the data obtained and saved through the two experiments and repeated the experimental process so that the system performance tended to the local optimum.

### 3.1. Simulation experiment under 100%-BMCR

The controlled object was \( \frac{5.93 \times 10^3 s^2 + 155.5s + 1}{s} \), the zero-order discretization of this model was conducted, the sampling time was \( T = 1s \), the iterative step size was \( \gamma_i = 0.1 \), and \( \lambda = 1 \). The performance requirement of control system should be satisfied by updating the controller parameters for 15 times. The changes in the output response of closed-loop system after the controller parameter vector was updated each time are shown in Figure 8. It could be seen that as the iteration process proceeded and the controller parameters were continuously updated, the overshoot of system output response became smaller and smaller, the tuning process lasted shorter and shorter time, and the speed was elevated obviously. The changes in the control signal after the controller parameter vector was updated each time are displayed in Figure 9. It could be observed that with the implementation of iteration, the control signal was continuously reduced, thus ensuring the optimization of system output response. The change curves of controller parameters and control index \( J \) in each iteration process are presented in Figure 10, from which it could be known that as the iteration process was continued, the performance index of the control system was continuously reduced until satisfying the user requirements, and the change laws of controller parameters in the iteration process were of certain guiding significance to the tuning of controller parameters in engineering practice.

![IFT-PID Control System](image)

Figure 7. IFT-PID Control System
Figure 8. Changes in Output Response of Closed-Loop System After Each Updating Process of Controller Parameter Vector

Figure 9. Changes in Control Signal After Each Updating Process of Controller Parameter Vector
Figure 10. Change Curves of Controller Parameters and Control Index $J$ in Each Iteration Process
(a) Change Curve of PID Parameter $K_p$; (b) Change Curve of PID Parameter $K_d$;
(c) Change Curve of PID Parameter $K_i$; (d) Change Curve of Control Index $J$
4. Conclusion
In this study, the theory of IFT method was introduced in detail. Next, IFT was integrated with the traditional PID controller to form an IFT-PID controller. The concrete control system design and simulation were implemented by selecting the first-order inertial plus pure lag object and second-order inertial object. The simulation results manifest that this method can be successfully applied to controlled objects with great inertia and large lag. It is indicated that the tuning method proposed in this study is of evident superiority in comparison with the traditional PID tuning method. Moreover, this method is not only applicable to the parameter tuning of PID controller, but moreover, only if a reasonable index is given, it can gradually update the parameter vector of any controller with known structure through the iteration process and finally achieve the local optimum of the control index.

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