Application of Improved Generalized Predictive Control in Main Steam Temperature of Thermal Power Boiler

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Abstract: For the main steam temperature control object of thermal power unit, it has the characteristics of time-varying, strong coupling, nonlinearity and large disturbance. The improved generalized predictive control is applied to its control system. The method not only retains the basic features and advantages of the generalized predictive control algorithm, but also has a simple algorithm, which does not require a large number of calculations of the matrix, thereby reducing the amount of online calculation, ensuring the rapidity of the system, and enabling the input to be well controlled. Within the scope of the constraint. Finally, through simulation analysis and engineering application, the improved generalized predictive control proposed in this paper has the advantages of small overshoot, short adjustment time and strong anti-interference ability, which effectively improves the stability of the main steam temperature control system.

1. Introduction

Main steam temperature is one of the main parameters of boiler steam control process monitoring and control. Its excellent control effect has important practical significance for improving thermal efficiency and safe and economic production of units.[1-3]If the main steam temperature is too high, the mechanical strength of metal parts such as main steam pipeline, speed regulating valve and cylinder will be reduced, thus threatening the safety of the unit; if the main steam temperature is too low, the thermal efficiency of the unit will be reduced.[4-5]Therefore, the main steam temperature must be strictly controlled so that it can be maintained near the given value, that is, the temperature fluctuation changes at the set value of 5°C.

At present, from the point of view of safe operation, conventional PID control strategy is widely used to reduce temperature. However, there are many factors affecting the main steam temperature, such as water flow rate and steam flow rate, and the dynamic characteristics of the main steam temperature object vary with the operating conditions.[6] Therefore, conventional PID control is difficult to achieve good control effect. In recent years, there are more and more researches on the main steam temperature of boilers at home and abroad. Such as predictive control [7], fuzzy control [8], and neural network control [9]. Reference [7] applies the improved dynamic matrix algorithm to the main steam temperature control system, which improves the dynamic performance of predictive control, but does not verify the model mismatch. Reference [8] combines fuzzy control with PID control, and designs a fuzzy self-tuning PID controller to continuously adjust the PID parameters according to the change of output. But in essence, it is a variable parameter PID control, which cannot effectively overcome the influence of large inertia of main steam temperature on the control system. Reference [9] Aiming at the important parameter of superheated steam temperature in thermal power plant, an improv-ed model control scheme is proposed based on optimizing the parameters of the controller.

However, the scheme has only been simulated, and has not been put into engineering test. Therefore, through the study of the main steam temperature control system of thermal power boilers, this paper proposes an improved generalized predictive control strategy, which is verified by simulation and engineering application. The results show that the strategy improves the stability of the system and has strong practicability.

2. Dynamic Characteristics of Main Steam Temperature

The main steam temperature system consists of a drum, a primary superheater, a primary water spraying desuperheater, as eco-ndary superheater and a secondary water spraying desuperheater. The specific structure of the system is shown in Figure 1[10].

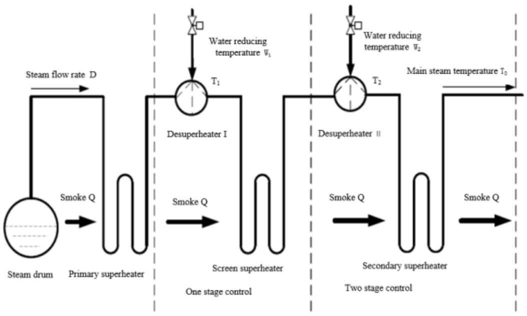

Fig.1 Production process of main steam

From Figure 1, it can be seen that the main factors affecting the main steam come from three aspects: steam flow disturbance, flue gas disturbance and temperature-reducing water disturbance. When D changes, the convection coefficient of super-heater will change, which leads to the change of steam tempera-Ture. When Q changes, flue gas velocity and steam temperature change along the whole super-heater almost simultaneously, but Q changes can affect the main steam temperature only through the tube wall of the super-heater.

The change of W is the main reason for the change of main steam temperature. It is also widely used in factories nowadays. Because the super-heater pipeline of large boilers is very long, the delay and inertia of the control object are relatively large when the desuperh-eated water is disturbed.[11]

Based on the dynamic characteristics of main steam temperature under the disturbance of cooling water flow rate, the mathematical model of the controlled object can be obtained by using least square identification method, which is generally expressed by the first or more order inertial link transfer functions with pure lag. The model of multi-order inertia plus pure delay for the main steam temperature transfer function is assumed as follows:

$$G(s)=\frac{b_0 s^m+b_1 s^{m-1}+\cdots+b_{m-1}s+b}{s^n+a_1 s^{n-1}+\cdots+a_{n-1}s+a_n}e^{-\tau s}(m<n) \tag{1}$$

By discretizing the zero-order holder, the following results are obtained:

$$G(z)=P(z)z^{-d}=\frac{B(z^{-1})}{A(z^{-1})}z^{-d} \tag{2}$$

In the formula:

$$A(z^{-1})=1+\bar{a}_1 z^{-1}+\bar{a}_2 z^{-2}+\cdots+\bar{a}_{na}z^{-na}$$
$$B(z^{-1})=\bar{b}_0+\bar{b}_1 z^{-1}+\bar{b}_2 z^{-2}+\cdots+\bar{b}_{na}z^{-nb}$$

The difference equation is as follows:

$$y(h)=-\sum_{i=1}^{na}\bar{a}_i y(k-i)+\sum_{i=1}^{nb}\bar{b}_i u(k-i-d-1) \tag{3}$$

3. Improved Generalized Predictive Control

Generalized predictive control (GPC) was proposed by D. W. Clarke et al.in 1987.It includes three basic features: prediction model, rolling optimization and feedback correction. It shows excellent control performance and is considered to be one of the representative pre- dictive control algorithms. It has been widely used in most industrial sites with time-delay phenomena, with remarkable economic bene-fits [12-15].

3.1 Prediction Model

The linearized CARIMA model of the main steam temperature control system for thermal power boilers can be expressed as:

$$A(q^{-1})y(k) = B(q^{-1})u(t-1) + \frac{C(q^{-1})\xi(k)}{\Delta} \tag{4}$$

Among them:

$$A(q^{-1}) = 1 + a_1 q^{-1} + a_2 q^{-1} \cdots + a_{na} q^{-n_a}$$
$$B(q^{-1}) = b_0 + b_1 q^{-1} + b_2 q^{-2} \cdots + b_{nb} q^{-n_b}$$
$$C(q^{-1}) = 1 + c_1 q^{-1} + c_2 q^{-2} \cdots + c_{nc} q^{-n_c}$$

It's a back ward operator, i.e. $q^{-1}y(k) = y(k-1)$, $q^{-1}u(k) = u(k-1)$; $\Delta = 1 - q^{-1}$ is backward difference operator, k is the minimum pure lag step and minimum value is 1.

3.2 Rolling Optimization

GPC is selected with the following objective functions:

$$\begin{aligned} J = & \sum_{j=1}^{N} \left[y(k+j) - \omega(k+j) \right]^2 \\ & + \sum_{j=1}^{M} \lambda(j) \left[\Delta u(k+j-1) \right]^2 \end{aligned} \tag{5}$$

Among them, N is the control time domain, the M is control length, the $\lambda(j)$ is control weighting coefficient ,generally take the constant and $y(k+j)$ is the output of the main steam temperature control system and the $\omega(k+j)$ is reference trajectory.

3.3 Output Prediction

In order to predict the output of the first step, the recursive algorithm is generally used to solve the Diophantine equation, as shown in the reference [15]. The predicted main steam temperature output of the first step can be expressed as:

$$\begin{aligned} \hat{y}(k+j) = & G_j(q^{-1})\Delta(k+j-1) + \\ & F_j(q^{-1})y(k) \end{aligned} \tag{6}$$

Among them:

$$G_j(q^{-1}) = E_j(q^{-1})B(q^{-1})$$
$$E_j(q^{-1}) = 1 + e_j^1 q^{-1} + \cdots + e_j^{j-1} q^{-(j-1)}$$
$$F_j(q^{-1}) = f_j^0 + f_j^1 q^{-1} + \cdots + f_j^{n_a} q^{-n_a}$$

Formula (3) can be written as

$$\hat{Y} = G\Delta u + f \tag{7}$$

In the formula:

$$\hat{Y} = [y(k+1), y(k+2), \cdots, y(k+N)]^T$$

$$\Delta U = [\Delta u(k), \Delta u(k+1), \cdots, \Delta u(k+N-1)]^T \ G = \begin{bmatrix} g_0 & & & 0 \\ g_1 & g_0 & & \\ & \vdots & & \\ g_{N-1} & g_{N-2} & \cdots & g_0 \end{bmatrix}$$

3.4 Optimal Control Rate

The softened reference trajectory vector is written as follows:

$$W=[w(k+1),w(k+2),\cdots,w(k+n)]^T$$

Then the objective function can be rewritten as follows:

$$J=(y-w)^T(y-w)+\lambda\Delta u^T\Delta u \tag{8}$$

In order to obtain the optimal control rate

and derivative, the optimal control rate of GPC can be obtained.

$$\Delta U=(G^TG+\lambda I)^{-1}G^T[w-Fy(k)] \tag{9}$$

In the actual control, in order to be able to adjust the amount of control in real time, only the $(G^TG+\lambda I)$ first line g^T added to the control system, ie $u(k)=u(k-1)+g^T(W-r)$.

From the above analysis, it can be seen that the traditional GPC needs matrix inversion operation, which requires a large amount of calculation and is not suitable for real-time control systems requiring fast response. Therefore, this paper adopts the Stepped generalized predictive control (SGPC) algorithm. By imposing the constraints of ladder control on the future control variables, the complex matrix operation is avoided, the operation process is simple and the response is fast. At the same time, the stability and anti-interference ability of the algorithm are improved, which can well meet the real-time requirements of the control system.

SGPC is to introduce the strategy of stepped control into GPC, so that the future control increment in GPC is proportional, as follows:

$$\frac{\Delta u(k+1)}{\Delta u(k)}=\beta \tag{10}$$

Among them β is the step factor.

SGPC also uses model (4). Based on GPC, stepped control strategy is introduced:

$$\begin{cases}\Delta u(k)=u(k)-u(k-1)=\delta\\ \Delta u(k+1)=u(k+1)-u(k)=\gamma\delta\\ \vdots\\ \Delta u(k+N_u-1)=u(k+N_u-1)-\\ u(k+N_u-2)=\gamma^{N_u-1}\delta\end{cases}$$

Which is

$$\Delta U=(1,\gamma,\cdots,\gamma^{M-1})^T\delta \tag{11}$$

Then optimal predictive control output value $\hat{Y}=G\Delta u+f$ also changed, let $G^*=G\Delta U$,that is to say

$$G^*=\begin{bmatrix}g_0 & & & \\ g_1 & g_0 & & \\ \vdots & \vdots & \ddots & \\ g_{N-1} & g_{N-2} & \cdots & g_0\end{bmatrix}[1,\beta,\cdots,\beta^{M-1}]^T$$

$$=\begin{bmatrix}g_0\\ g_1+\beta g_0\\ \vdots\\ g_{N-1}+\beta g_{N-2}+\cdots+\beta^{M-1}g\end{bmatrix}$$

Then the formula (7) becomes:

$$\hat{Y}=G^*\delta+f \tag{12}$$

After substituting equations (11) and (12) into the objective function for integration, there is the following formula:

$$\begin{aligned} J &= (G\Delta u + f - W)^T (G\Delta u + f - W) + \\ &\lambda(1+\beta^2+\cdots+\beta^{2(M-1)})\Delta u^2 \end{aligned} \tag{13}$$

And make $\frac{\partial J}{\partial \Delta u} = 0$, it can be obtained that:

$$\Delta u = \left[G^{*T} G^{*} \lambda(1+\beta^2+\cdots+\beta^{2(M-1)})\right]^{-1} G^{*T}(W-f) \tag{14}$$

In Formula (14)

$$G^* = \begin{bmatrix} g_0 \\ g_1 + \beta g_0 \\ \vdots \\ g_{N-1} + \beta g_{N-2} + \cdots + \beta^{M-1} g_{N-M+1} \end{bmatrix}$$

Can be seen from above G^* is $N \times 1$ Column vector, but G is $N \times N$ matrix, In this way, the matrix calculation in the algorithm is transformed into vector calculation, which greatly reduces the amount of calculation.

4. Simulation Analysis

In order to verify the control effect of the proposed method, MATLAB software is used to simulate. The transfer function of different loads is adopted in the simulation, that is to say, the transfer function under 50% load is $\frac{1.07}{(150\text{s}+1)^2} \cdot e^{-183s}$; the transfer function under 50% load is $\frac{1.22}{(60s+1)^2} e^{-65s}$.According to equations (2) and (3), itistransf-ormed into the relative difference equation and the main steam temperature control system model of the thermal power boiler is established in the Simulink environment. Based on this model, two methods of generalized predictive control and SGPC proposed in this paper are used for simulation and comparison and the parameters selected areas follows: Period $T = 1s$,predicted time domain $N = 400$. Control time domain $M = 4$ .It can be seen from Fig.3 that under 50% load condition, the stepwise generalized prediction has no overshoot when no interference is added, the adjustment time is 140s,the GPC overshoot is 9.4%,and the adjustment time is 500s;When 10% interference is added at 1000s,the main steam temperature control system is controlled by stepwise generalized prediction. The overshoot is5.21% and the adjustment time is281.61s.

When the GPC is adopted, the overshoot of the main steam temperature control system is 12.9%,and the regulation time is 583s.It can be seen from Fig.4 that under the 100% load condition, the stepwise generalized predictive control has no overshoot when no interference is added, the adjustment time is 187.5s,and the GPC overshoot is 13.1%,and the adjustment time is 625s.When the interference is added at 1000s,the SGPC overshoot is 4.9%, the adjustment time is 312s,and the GPC overshoot is 14.2%,and the adjustment time is 562.5s.It can be seen that the SGPC proposed in this paper has strong stability and anti-interfe-rence ability. The specific simulation diagram is shown below.

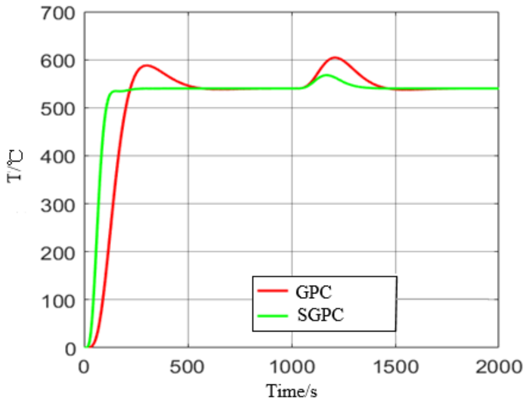

Fig.2 Adding interference simulation diagram (50%load)

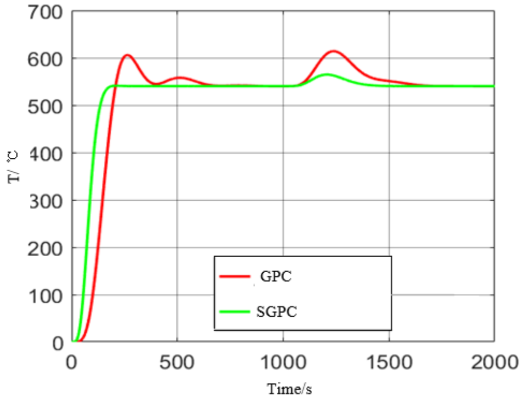

Fig.3 Adding interference simulation diagram (100%load)

In the actual production process, the main steam temperature control system is vulnerable to external interference, thus in a mismatch state. In this paper,50% load and 100% load transfer function K, T and τ are increased by 30%, respectively. The effectiveness of the pro-posed control strategy is verified in case of model mismatch. It can be seen from Fig.5 that under the 50% load condition, when the SGPC strategy is adopted, the overshoot is 2.8% and the adjustment time is 69.76s.When 10% interference is added in 1000s,the overshoot is 5.9% and the adjustment time is244.18s.When the GPC strategy is used, the overshoot is 25.5% and the adjustment time is 906.9s.

When 10% interference is added to 1000s,the overshoot is 17.2% and the adjustment time is 697.6s.It can be seen from Fig. 6 that under the 100% load condition, when the SGPC is used, the overshoot is 4.5% and the adjustment time is 94.59s.When 10% interference was added at 1000s, the overshoot was 5.8% and the adjustment time was 324.32s.When the GPC is used without interference, the overshoot is 27.57% and the adjustment time is 750s.When the interference is added, the overshoot is 20.37% and the adjustment time is 561.22s.From the above analysis, the SGPC strategy proposed in this paper can solve the model mismatch problem well. The specific simulation diagram is shown below.

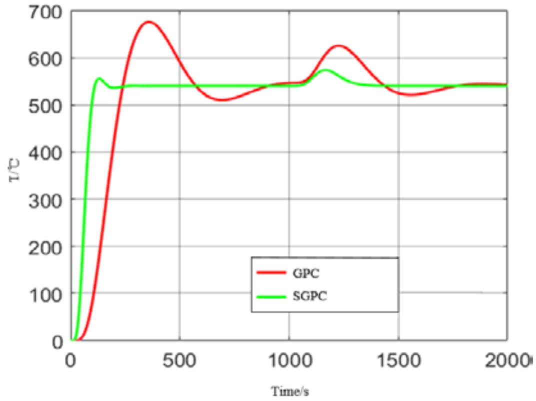

Fig. 4 Adding interference simulation diagram under model mismatch (50% load)

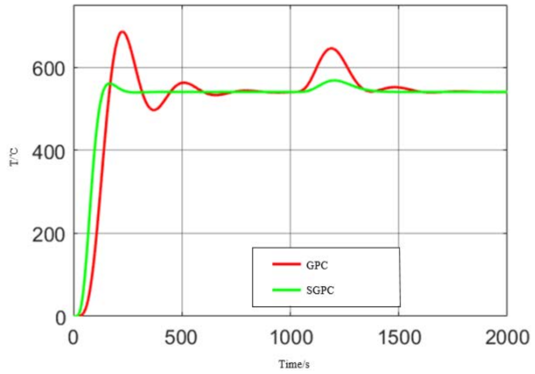

Fig 5. Adding interference simulation diagram under model mismatch (100% load)

In this paper, we take a 150t power gene-ration boiler in a steel power generation 3 workshop as the practical object. Its control system is the Zhejiang University central control DCS system, and the rated power generation is 42MW.The automatic combustion optimization control system designed by this project uses the OPC protocol to communicate with the user's existing DCS system. Based on the existing basic control instruments of the power generation boiler, there is no need to add additional hardware and existing to the original control system. The control valve control circuit makes any changes to ensure all the functions of the original system, only the configuration settings are added to the original DCS system, and the dual-machine undisturbed single-loop switching and one-button switching functions are designed to ensure that the two systems can be Freely switch, or automatically switch to the original DCS system when the optimization system fails, and does not affect the normal operation of the user's original control system when the automatic system is cut out. The block diagram of the connection between the optimized control system and the original DCS system is shown in Figure 6.

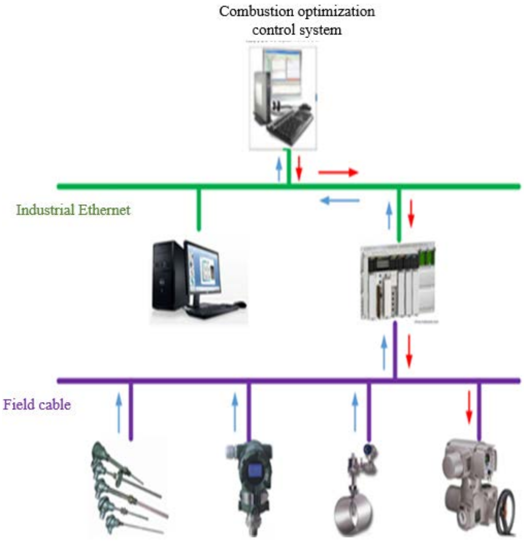

Fig.6 Structural diagram of combustion optimization control system

The combustion optimization control system uses the Kepware OPC software for data communication and the force control configuration software for algorithm and configuration programming. Figure 7 is the main steam temperature curve of step general-ized predictive control and figure 8 is the main steam temperature curve of generalized predi-ctive control. The equilibrium point of the main steam temperature is 480℃, and the setting time is one hour. It can be seen from Fig.7 that when the main steam temperature control loop is put into the algorithm designed in this paper, the main steam temperature curve is more stable and there is no big fluctuation, and 50% interference is added at 3 p.m., the main steam temperature fluctuation is very small, the overshoot does not exceed ± 5 ℃, and quickly restores to a stable state. As can be seen from Figure 8, when the GPC algorithm is adopted, the time for the main steam temperature to recover to the stationary position is slow and the fluctuation is greater when disturbance is added. Therefore, the stepped generalized predictive control strategy proposed in this paper can adjust the main steam temperature faster than the traditional GPC, and has good control quality.

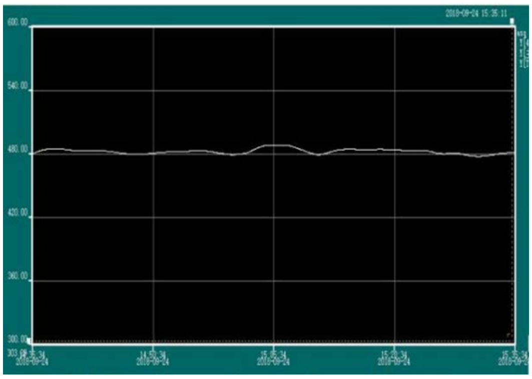

Fig 7. SGPC of main steam temperature

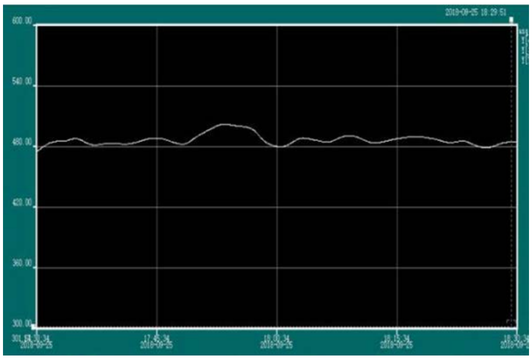

Fig 8. GPC of main steam temperature

5. Conclusion

Aiming at the problems of non-linearity and large time delay in temperature control of steam super-heater, an improved GPC strategy is proposed in this paper, which overcomes the complex operation of traditional GPC. The simulation analysis and engineering experiments show that the method effectively improves the control problem of model parameter change and time-delay system, and has good anti-interference, and achieves satisfactory control effect.

Acknowledgements

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