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Multi-model Switching Predictive Functional Control of Boiler Main Steam Temperature

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Abstract: Main steam of the power plant is typical great inertial and long-time delay component. The dynamic characteristic of main steam temperature is greatly changed when load of the boiler varies. Traditional Proportional Integral Derivative (PID) control and fixed model predictive functional control neither can't get satisfying control effect such as lower control precision, higher fluctuation of temperature and so on. In this study, the multi-model predictive functional control is proposed for weakening the effect of the great inertial and long-time delay and enhancing control precision of main steam temperature. Simulation experiments with different loads shows that the proposed method is better than the traditional PID control and fixed model predictive functional control.

Key words: Main steam temperature, great inertial, long-time delay, predictive functional control, multi-model switching

INTRODUCTION

Main stream temperature of boilers at heat-engine plant is an important parameter of the thermal process, it affects the economical efficiency and security of boiler operation. Low temperature affects the operating efficiency of the unit, high temperature affects the operation security of turbines, superheaters and other devices. The temperature deviation from set value should be less than 5°N (Wang *et al*., 1993). However, considering the great inertia, long-time delay of the main stream temperature of boiler and its parameters change with different situations, the control effect of traditional cascade-stage PID based on fixed model will not be ideal enough.

Wang *et al*. (1993) and Lv (1995) combine the neural network and fuzzy control theory with cascade-stage PID control and adjust the parameters of PID control with the changes in output. But it is still the PID control of varying parameters essentially and can not overcome the impact of main stream temperature on control system, causing the long debug time, lack of stability margin and even the shock of system. Thus, the stability of the system will be influenced. Wang *et al*. (2002) uses the predictive control to overcome the impact of great inertia on control system but the prediction model is fixed. When it comes to the change of operation duty of boiler, the model can not adapt to the change of the model of main stream temperature, leading to the poor effect. The key of the control of main stream temperature lies in the elimination of the effect of great inertia, long-time delay and time varying at the meantime.

This study will solve this problem by combining predictive functional control with multi-model switching. Predictive functional control is the third generation model predictive control algorithm, it stresses the structure of controlled variables, reduces the on-line calculation and leaves only several linear weighting coefficients to calculate. Besides, it has fast tracking, high precision and other characteristics. Using predictive functional control to predict the changes of output variation can overcome the impact of great inertia, long-time delay on control system; but the system performance of predictive functional control will decline largely when the changes of parameters are too large (Kutze *et al*., 1986; Richalet *et al*., 1987). For this reason, establishing multiple main stream temperature models in advance on different occasion, designing corresponding predictive functional control and switching among the different models in line with the variation of working condition can eliminate the impact on control system.

MULTI-MODEL SWITCHING PREDICTIVE FUNCTIONAL CONTROL

Structure chart of multi-model switching predictive functional control of mainstream: There are many factors that can affect the main stream temperature of boilers:

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boiler load, gas temperature and flow rate, the temperature-decreased flux, the position of flame kernel, temperature of feed water and so on. To overcome these disturbances and obtain more perfect control effect, the cascade-stage control structure combined with multi-model smooth switching predictive functional control is used to design the control structure which is presented in Fig. 1. The controlled objection W2(s) in Fig. 1 is the transfer function of leading segment, the regulating variable u of the valve of spray water temperature reducing device is the input, the output is the stream temperature θ_1 of the exit of desuperheater; the controlled objection $W_1(s)$ is the transfer function of inert area, the input is θ_1, output is the main stream temperature θ_2. Let's take the vice regulating loop and inert area as a whole and name the constitutive controlled members after the generalized controlled members of main stream temperature. $G_1 \ldots G_n$ are m generalized controlled objects of main stream temperature under typical working condition which equal with the one-order inertial combining delay component. $PFC_1 \ldots PFC_n$ are the predictive functional controls under every working condition.

The operating principal of control system is using the control signal of every second in $G_1 \ldots G_n$ and controlled process, then calculating the output of model $G_1 \ldots G_n$, detecting the procedural output and comparing the output of $G_1 \ldots G_n$ with procedural output to feed back to multi-model switching module and corresponding predictive functional control $PFC_1 \ldots PFC_n$, switching to appropriate control on the basis of multi-model switching tactics.

The control principle of multi-model switching predictive functional control: Predictive Functional Control (PFC) shares three essential characteristics with other predictive control algorithms: predictive model, receding horizon, feedback compensation. What makes it different from the others is that it regards the input structure of control as the key in affecting control system.

The typical system in industrial control is one-order inertial combining delay component which is used to approximate the common control process. In the main stream temperature control, generalized controlled objects constituted by every link in the box of Fig. 1 can be used in one-order inertial combining delay component to approximate (Wang *et al.*, 2002), so the predictive model of predictive functional control can be:

$$W_m(s) = \frac{K_m}{T_m s + 1} e^{-T_d s} \tag{1}$$

As for one-order inertial combining delay component, its output is obtained by the principal of predictive functional control:

$$u(k) = \frac{c(k+P) - \alpha^P c(k) - (1-\alpha^P) y_{pav}(k)}{K_m (1-\alpha_m^P)} + \frac{y_m(k)}{K_m} \tag{2}$$

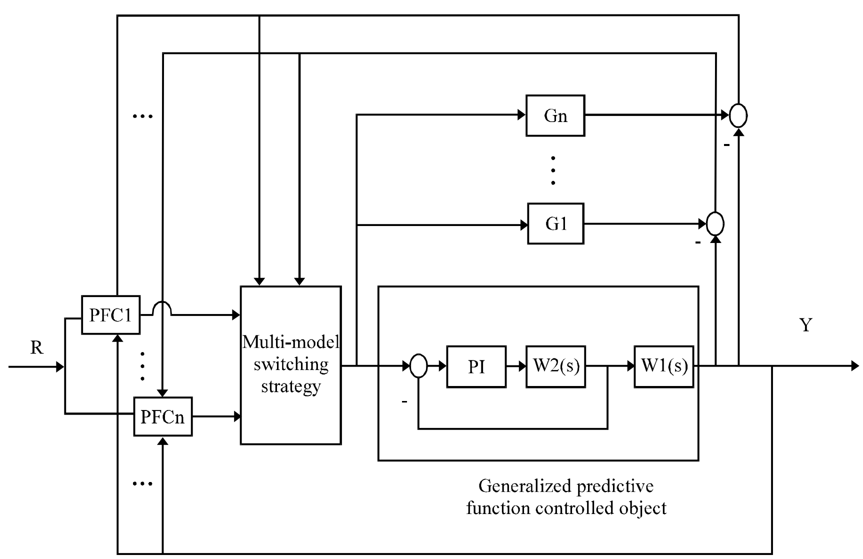

Fig. 1: Structure chart of multi-model switching predictive functional control of main steam, PFC_i (i = 1, 2,..., n) is the predictive functional controller, PI is the proportional integral controller; W2(s) is the transfer function of leading segment controlled object; W1(s) is the transfer function of inert area; G_i (i = 1, 2,..., n) are generalized controlled objects of main stream with the different working condition

In the last-written formula:

$$\alpha_m = e^{-T_s/T_m}, \beta = e^{-T_s/T_r} \quad (3)$$

$$Y_{pav}(k) = y(k)+y_m(k)-y_m(k-D) \quad (4)$$

In formula 2 P is the length of predictive time domain and in formula 3, T_s is sampling period; T_r is the lag coefficient of reference trajectories of predictive function control. In formula 4, $D = T_m/T_s$ reflects the lag degree of one-order inertial combining delay component comparing sampling period; $y_m(k)$ is the output of k.

Formula 2 is the output controlled variable of control at k, u(k) can make the difference between procedural output and controlled reference value reach the smallest one at k+P. The detailed derivation process in can be acquired by Richalet *et al*. (1987).

The approach to one-order inertial combining delay component of main steam generalized controlled object: Once the predictive function control algorithm of one-order inertial combining delay component in the previous section is obtained, next one-order inertial combining delay component of main steam generalized controlled object is demanded when the main stream temperature is controlled by PFC.

Now a boiler with 30% workload is regarded as an example, one-order inertial combining delay component of main steam generalized controlled object of this boiler can be approximated. The transfer function of leading segment is $8.07/(24s+1)^2$, that of inertial area is $1.48/(46.6s+1)^4$. As shown in Fig. 2, cascade-stage method is used to control system and PI control to adjust in inner loop, $\delta = 0.0694$, $T_i = 12$, the transfer function which equals one-order inertial combining delay component is obtained by simulation:

$$G_m(s) = \frac{1.48}{108.5s+1} e^{-85s}$$

The comparison curve of them is shown in the Fig. 2. The two curves shown in Fig. 2 are so close that they can be used to replace generalized controlled objects approximately with one-order inertial combining delay component.

The five given typical transfer functions of leading segment and inertia area at working load point of this boiler after simulation experiment (Han *et al*., 2003) in which the inner loops use the same PI control and the parameter of control is $\delta = 0.0694$, $T_i = 12$.

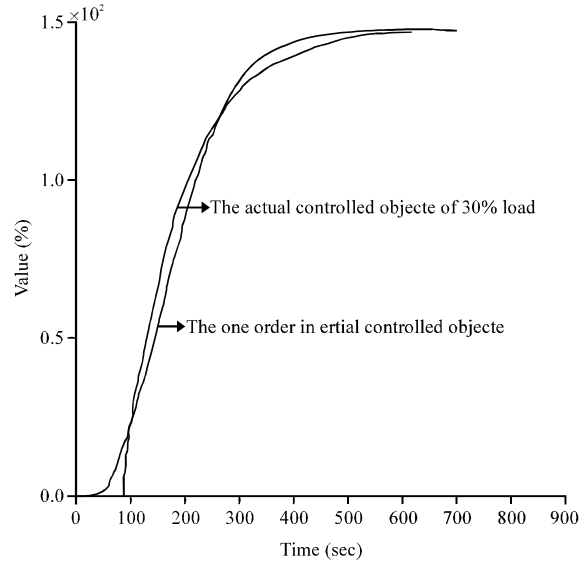

Fig. 2: Response of main steam generalized controlled object of 30% load and one-order inertial combining delay component

Multi-model switching strategy: The disturbances which affect the main stream temperature model are mainly: the temperature and pressure and flux of main stream. The changes in temperature have the smallest effect on the parameters of model, the effect of pressure is middle and the effect of flux is the biggest. Comparing with the latter, the effect of temperature may be neglected in the theory analysis. Main stream pressure and flux are coupling and the changes in flux can cause the changes in pressure (Fan *et al*.,1997), so the reasons for the changes in main stream temperature model is the changes in operating load of boiler.

When the operating load of boiler changes, if the initial model is used still as the effect of predictive control, the effect will be worse, even can trigger the instability of control system. So the models under different working condition ought to be adopted and design the corresponding PFC control and use the multi-model switching tactics to switch predictive control model to control which is closest to the practical model to ensure the best control effect.

The index of multi-model is:

$$J_i(k) = \alpha e_i^2(k) + \beta \sum_{j=1}^{L} \rho^{k-j} e_i^2(k-j), i = 1, 2, \cdots, N \quad (5)$$

$e_i(k)=y(k)-y_i(k)$ also known as $e_i(k)$ is the difference between procedural output and output of model i at, α, β

are weight and represents the impact of current and past difference between procedural output and model on switching index respectively, N represents the number of the model, L represents the length of error which effects the switching of index, ρ represents memory effect, J_i represents the degree of difference between control procedure and ith model, the smaller the difference is, the distance between process and model is closer.

To avoid the instability from switching randomly, the hysteretic switching algorithm is used which is presented by Middleton *et al.* (1988). Suppose that it is control i in the control system which is controlling, every time after sampling procedural output, formula 6 can be got:

$$J_j(k) = \min \{J_l(k)\},\ l = 1, 2,..., N \tag{6}$$

Find the model number j which has the smallest switching index, if $j \neq i$, the switching tactics are used to judge the necessity of switching, if:

$$J_j(k)+\rho \leq J_i(k) \tag{7}$$

Then switch to the jth control or still use the ith control, in which ρ is delay factor.

SIMULATION EXPERIMENTS

The comparison between single-model predictive function control and traditional PID control: First, the traditional PID and PFC control algorithm are applied to simulate the main stream temperature model and compare the results. The two algorithms are both cascade-stage control and PI control for inner loop, the parameter of its control is $\delta = 0.0694$, $T_i = 12$. The control parameter of PID adopts critical proportion band (Guo and Wang, 2009) to get the parameters in the three stages of the proportional differential and integration; the one-order inertial combining delay component in Table 1 (it is the option table for control model of predictive function) which equals the generalized predictive object is predictive model. Table 2 gives the proportions, differentials, integrations of the parameters of PID control and the parameters of PFC control under different loads. Figure 3-5 show optimum control effect by changing T_s, T_r and P of predictive function control under every load. The impact of these three parameters on predictive function control can be seen in formula 2-4.

From the simulation curves above, It conclude that the difference of control effect between PID control and PFC control and the overshoot of PFC are both small and when the boiler is operated under low load and small effect of inertia; the inertia of (Table 2) PID control and PFC control parameters of different main stream temperature is obvious when the boiler is under overload, this is because that predictive function can percept the

Table 1: One-order inertial combining delay component of main steam generalized controlled object

The load of boiler (%)	Leading segment	Inertia area	Equivalent one-order inertial combining delay
30	$\frac{8.07}{(24s+1)^2}$	$\frac{1.48}{(46.6s+1)^4}$	$G_m(s) = \frac{1.48}{108.5s+1}e^{-85s}$
44	$\frac{6.62}{(21s+1)^2}$	$\frac{1.66}{(39.5s+1)^4}$	$G_m(s) = \frac{1.66}{93.02s+1}e^{-70s}$
62	$\frac{4.35}{(19s+1)^2}$	$\frac{1.83}{(28.2s+1)^4}$	$G_m(s) = \frac{1.83}{55s+1}e^{-65s}$
88	$\frac{2.01}{(16s+1)^2}$	$\frac{2.09}{(22.3s+1)^4}$	$G_m(s) = \frac{2.09}{48.9s+1}e^{-44s}$
100	$\frac{1.58}{(14s+1)^2}$	$\frac{2.45}{(15.8s+1)^4}$	$G_m(s) = \frac{2.45}{30.5s+1}e^{-35.8s}$

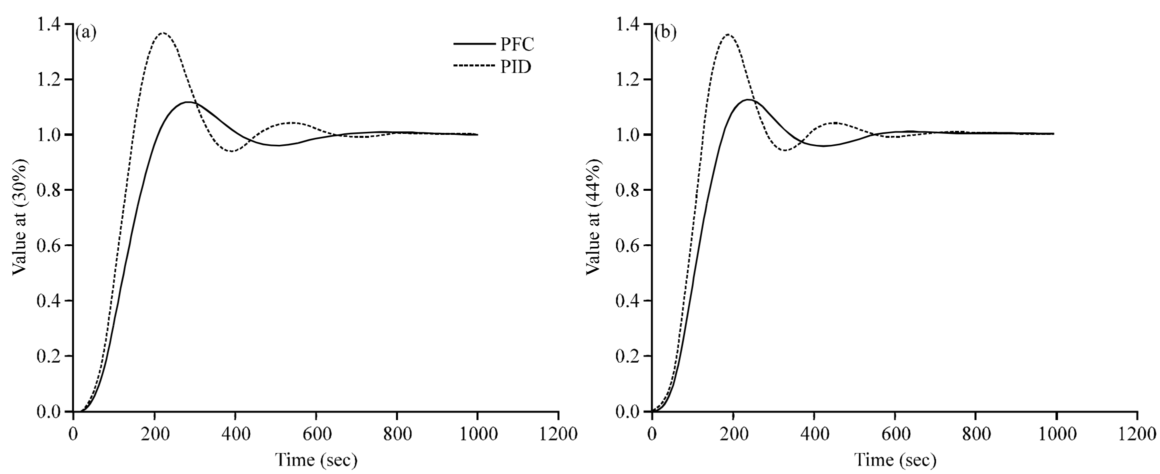

Fig. 3(a-b): Control effect of, (a) 30% and (b\) 44% load

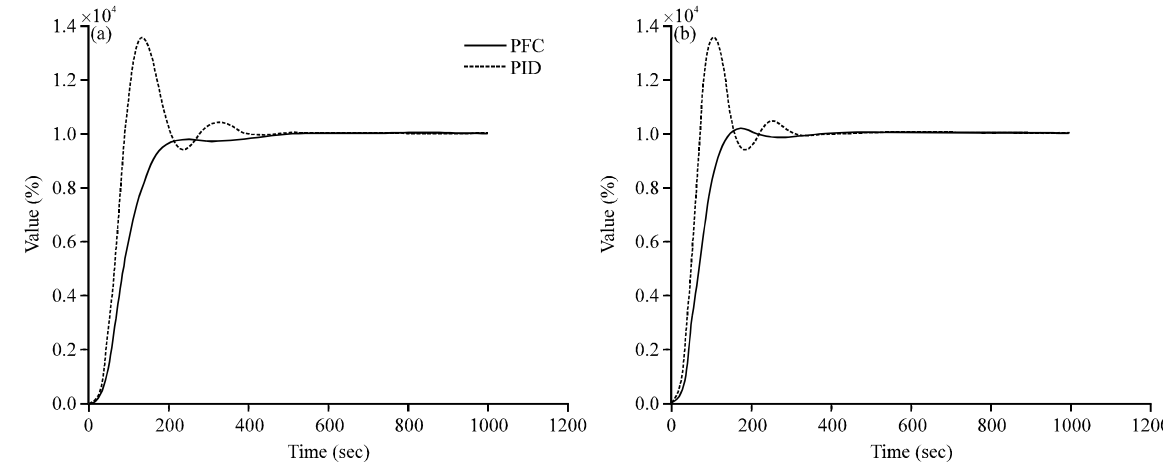

Fig. 4(a-b): Control effect of, (a) 62% and (b) 88% load

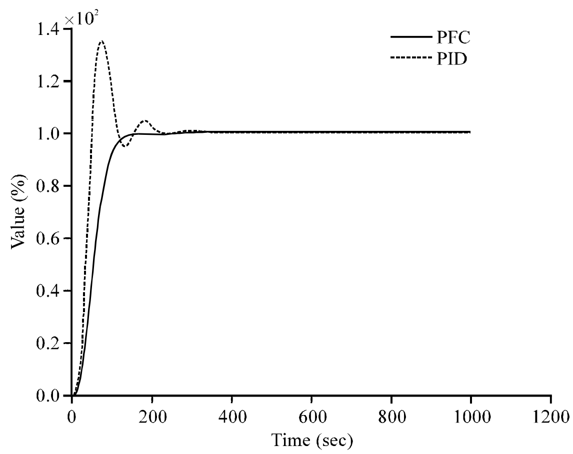

Fig. 5: Control effect of 100% load

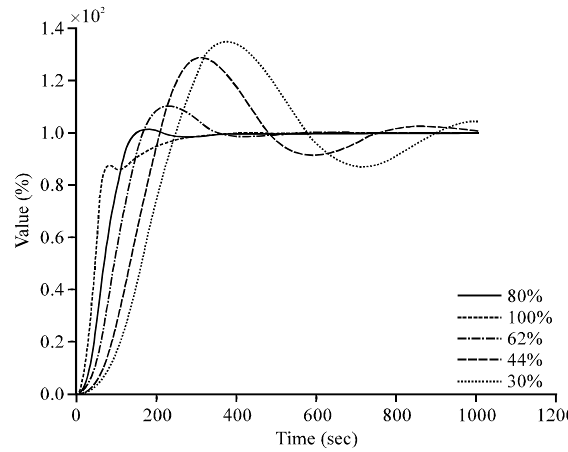

Fig. 6: Robustness analysis of predictive functional control

Table 2: PID and PFC control parameters of different load

The load of boiler (%)	The cascade-stage control parameter of PID	The cascade-stage control parameter of PFC
30	δ =0.629, T_i = 147, T_d = 36.75	T_s = 1, T_r = 1, p = 87
44	δ = 0.7084, T_i = 125, T_d = 31.25	T_s = 1, T_r = 1, p = 7
62	δ = 0.79067, T_i = 89, T_d = 22.25	T_s = 1, T_r = 1, p = 72
88	δ = 0.9189, T_i = 70.5, T_d = 17.625	T_s = 1, T_r = 1, p = 67
100	δ = 1.1111, T_i = 50.5, T_d = 12.62	T_s = 1, T_r = 1, p = 5

PID is the proportional integral derivative controller, PFC is the predictive functional controller, δ is proportion band, T_i is differential time, T_d is integration time, T_s is sampling period; T_r is the lag coefficient of reference trajectories of predictive function control, p is the length of predictive time domain

variation trend of output in advance by predictive model and the control can make regulation in advance. Then, the control effect of PFC is much better than PID. Thus, in this study, the predictive function control algorithm is chosen as the algorithm for main control in cascade-stage control.

Robustness analysis of single-model predictive function: The predictive function control algorithm is applied into real control which demands the knowledge of the precise or approximate model of controlled objects. For main stream temperature control system, when the control parameters under the specific load are known, the parameters of corresponding control vary with the loads or the control effect will be worse. Now take the boiler of 88% load as an example, the control parameters of PFC of optimum control effect can be obtained, the same control parameters are used to adjust the boiler model into other four known loads and then analyze the robustness of the system.

Based on the simulation results above, for single-model predictive function, by observing Fig. 5 and 6, the two conclusion are obtained: one is the output of the

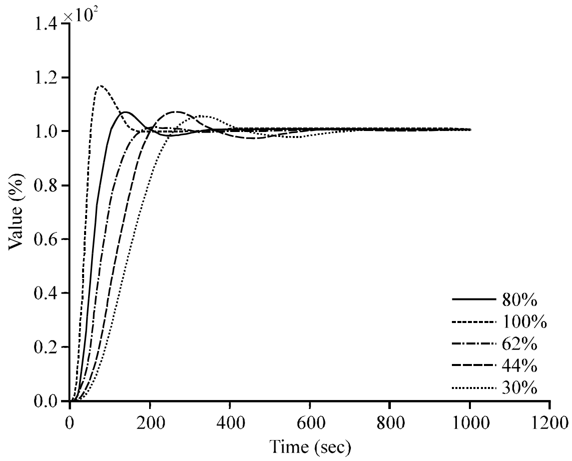

Fig. 7: Simulation analysis of multi-model predictive functional control

system will shock when the load goes up; the other is the response speed of control will slow down sharply when the boiler is under load. Therefore, the predictive function control of single-model can not deal with the large-range variation of boiler.

The simulation result of multi-model switching predictive function control: Since the single-model predictive function control can not overcome the impact of changes in load on main stream temperature, the multi-model switching tactics are adopted in this study to solve this problem. The control structure is presented in Fig. 1 and formula 2 for predictive function control, formula 3 for multi-model switching tactics, Fig. 7 for simulation curve.

From the simulation result above, it conclude that the multi-model switching predictive function control can still obtain preferable dynamic performance when the load of boiler changes. Therefore, the control scheme of multi-model switching predictive function can solve the puzzle in the main stream temperature of boiler.

CONCLUSION

These study combines predictive function control with multi-model switching which presents the multi-model switching predictive function control, provides the switching tactics and then apply it into the control of main stream temperature. Plenty of simulation experiments show that the main stream temperature control based on multi-model switching has preferable dynamic performance, strong robustness and easy algorithm. It can be implemented easily in engineering, so it has certain engineering practical value.

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