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PID Controller Parameters Tuning Based on Pole Assignment Optimal Prediction for Power Station Boiler Superheated Steam Temperature

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***Abstract*—In view of the long-time delay and large inertia of boiler superheated steam temperature control, this paper proposed a self-tuning control strategy based on Pole Assignment Optimal Prediction. Model parameters are identified by Least squares algorithm with forgetting factor, and then according to the estimation model of superheated steam temperature object, the PID parameters are tuned by designing the adaptive law with the method of Pole Assignment Optimal Prediction. Consequently the closed-loop system has desired characteristics; also this control strategy can solve the problem of the long-time delay of boiler superheated steam temperature. Finally the simulation results have shown the method has good dynamic and static control performances for this complicated superheated steam temperature control system, and meet the actual superheated steam temperature control requirements.**

***Index Terms*—Pole assignment, optimal prediction, forgetting factor, PID parameters tuning, superheated steam temperature.**

I. INTRODUCTION

PID control is widely used in industry, for larger nonlinear systems the parameters of control object often need to be tuned at different working points, and the tuning process is not easy, so the versatility is not strong for different objects. Fuzzy control [1], [2] and neural control [3], [4] for nonlinear system can achieve better control effect, but the establishment of fuzzy rules and the application of neural network model are still built on the basis of experience, and it is difficult to obtain the specific description of closed-loop control characteristics.

The pole placement algorithm is a commonly used design method with intuitively design and good dynamic performance, which can adapt to the unstable inverse system (non-minimum phase system) and open-loop unstable system. The method of pole placement based on input-output transfer function model is one of the mature control methods among the modern control theories. It can implement specified closed loop characteristics for linear time-invariant object and further improve the dynamic response and robustness.

For large delay object, Smith [5] firstly proposed a predictive controller which could improve the control quality. Palmor [6] and Watanabe [7] pointed out the defects in the practical applications, thus limiting its application. Keyser [8] proposed self-tuning predictive controller, especially the applications of self-tuning predictive PID controller were given, but its drawback is that the control parameters were also chosen by experience. This paper proposed a pole assignment optimal prediction self-tuning PID controller which combined online identification of the model parameters and the online design of the controller. The parameter identification used recursive least squares algorithm with forgetting factor, while the controller adopted pole assignment optical prediction algorithm. The method not only achieved the desired control characteristics, and for large delay problem of the superheated steam temperature but also obtained good control quality.

The superheated steam temperature of high temperature superheater for power station boiler was one of the main control parameters of the thermal control system. The control system mainly adopted convention cascade PID control. Under serious interference and varied working condition, it is difficult to achieve ideal control effect. Hence a lot of new control strategies which combined predictive control method and the traditional PID control appeared [9]-[12]. In this paper, the outer PID parameters tuning adopted the pole assignment optimal prediction algorithm, and combined the inner PID controller to control the superheated steam temperature.

The main research contents of the paper include the following three aspects. Firstly, aiming at the problem of model parameters estimation, we adopt the least squares algorithm with forgetting factor. It can effectively identify the parameters of superheated steam temperature. Secondly, aiming at the superheated steam temperature control system of Power Station Boiler, a cascade compound control strategy that combines an outer loop PID master controller adjusted with pole assignment optimal prediction algorithm and an inner loop PID auxiliary controller is adopted. Lastly, the simulation of this method is given in this passage. The result shows that the proposed method can achieve good static and dynamic performances.

II. THE PID CONTROLLER

A. The Continuous PID Controller

In a continuous control system, the PID controller can been express as

$$u(t) = K_p \left(e(t) + \frac{1}{T_I} \int_0^t e(t)dt + T_d \frac{de(t)}{dt} \right) \qquad (1)$$

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Use Laplace transform, so it can been written in transfer function form

$$\frac{u(s)}{e(s)} = K_p\left(1+\frac{1}{T_I s}+T_d s\right) \tag{2}$$

B. The Discrete PID Controller

In a digital system, in order to realize PID control, the continuous PID controller should been converted to discrete PID controller. If the sampling period is T_0, the discrete PID controller uses difference equation to express as

$$u(k) = K_P(e(k)+\frac{1}{T_I}\sum_{I=0}^{k} T_0 e(k-i)+T_d\frac{e(k)-e(k-1)}{T_0}) \tag{3}$$

Transform (3) by Z-translation

$$\begin{aligned} u(z) = K_P(e(z)+\frac{T_0}{T_I}\frac{1}{1-z^{-1}}e(z) \\ +\frac{T_d}{T_0}(e(z)-z^{-1}e(z))) \end{aligned} \tag{4}$$

The discrete pulse transfer function

$$\frac{u(z)}{e(z)} = \frac{r_0+r_1z^{-1}+r_2z^{-2}}{1-z^{-1}} \tag{5}$$

where,

$$\begin{cases} r_0 = K_P(1+T/T_I+T_D/T) \\ r_1 = -K_P(1+2T_D/T) \\ r_2 = K_P T_D/T \end{cases}$$

III. THE DESIGN OF THE LEAST SQUARES ALGORITHM PARAMETER ESTIMATOR

There are a lot of different model parameter identification algorithms, and the least squares algorithm is the most widely used identification algorithm in industrial control because of small online computation and high stability. With the growth of data, the data saturation of ordinary least squares will appear, and with a large amount of calculations, it will lead to a decline in the control of the system. In order to overcome this phenomenon, the recursive least square method with forgetting factor was adopted for the estimation of superheated temperature outer PID controller [13], [14].

The controlled object with Controlled Auto Regressive Moving Average (CARMA) model is expressed as

$$A(z^{-1})y(k) = z^{-d}B(z^{-1})u(k)+C(z^{-1})\xi(k) \tag{6}$$

$y(k)$ is system output, $u(k)$ is control quantity, $\xi(k)$ is the noise, d is the delay time of the system, $A(z^{-1})$ and $B(z^{-1})$ is weighted polynomial of the controlled object, $C(z^{-1})$ is weighted polynomial of the disturbance object.

$$\begin{cases} A(z^{-1}) = 1+a_1z^{-1}+\dots\dots+a_{(n_a)}z^{-n_a} \\ B(z^{-1}) = b_0+b_1z^{-1}+\dots\dots+b_{(n_b)}z^{-n_b}, (b_0 \neq 0) \\ C(z^{-1}) = 1+c_1z^{-1}+\dots\dots+c_{(n_c)}z^{-n_c} \end{cases}$$

where,

$$\begin{aligned} \theta &= [a_1, a_2, \dots a_{n_a}, b_1, b_2, \dots b_{n_b}]^T \\ \varphi^T &= [-y(k-1), -y(k-2), \dots - y(k-n_a), \\ &\quad u(k-d), u(k-d-1) \dots u(k-d-n_b)] \end{aligned}$$

This can be written in vector form

$$y(k) = \varphi^T\theta + C(z^{-1})e(k) \tag{7}$$

The observation vector φ^T and the estimation parameter vector θ were substituted into the recursive least squares formulas. So the parameters of the controlled object could be identified online.

With forgetting factor recursive least squares algorithm formula can be expressed as

$$\begin{cases} K(k) = \dfrac{P(k-1)\varphi(k)}{\rho+\varphi^T P(k-1)\varphi(k)} \\ \theta(k) = \theta(k-1)+K(k)[y(k)-\varphi^T(K)\theta(K-1)] \\ P(k) = \dfrac{1}{\rho}[1-K(k)\varphi^T(k)]P(k-1) \end{cases}$$

ρ is the forgetting factor. Its value is selected between $0.95-1$ by considering the time-varying parameters, disturbances and the order of the model. K is the gain vector. P is the estimation error covariance matrix.

IV. POLE ASSIGNMENT OPTIMAL PREDICTION SELF-TUNING CONTROL ALGORITHM

For linear system, pole distribution not only has an effect on the stability of the system, but also has a great influence on the system dynamitic performances such as rise time, overshoot and oscillation frequency etc. Therefore, as long as choose a feedback control law to make the closed-loop poles in the desired position, the closed-loop system performance will meet the prescribed performance index. This is the pole assignment design method [15]. Also in this passage the optimal prediction method is adopted to solve the delay problem in the process control.

By Diophantine equation $C(z^{-1})/A(z^{-1})$ in the object model which described in (6) can be decomposed into

$$\frac{C(z^{-1})}{A(z^{-1})} = F(z^{-1})+z^{-d}\frac{G(z^{-1})}{A(z^{-1})} \tag{8}$$

where,

$$\begin{cases} F(z^{-1}) = 1 + f_1 z^{-1} + \cdots + f_{d-1} z^{-d+1} \\ G(z^{-1}) = g_0 + g_1 z^{-1} + \cdots + g_{n-1} z^{-n+1} \end{cases}$$

Using (6) and (8), we can get

$$\begin{aligned} y(k+d) = \frac{G(z^{-1})}{C(z^{-1})} y(k) + \frac{B(z^{-1})F(z^{-1})}{C(z^{-1})} u(k) \\ + F(z^{-1}) e(k+d) \end{aligned} \tag{9}$$

$y[(k+d) \mid k]$ represents estimation value at the time of $(k+d)$ according to output value of k time.

The problem now is to find optimal prediction $y^*[(k+d) \mid k]$ in $y[(k+d) \mid k]$ to make the least prediction error variance, which satisfy the following formula

$$\begin{aligned} E\{y(k+d) - y^*[(k+d) \mid k]\}^2 \\ \le E\{y(k+d) - y[(k+d) \mid k]\}^2 \end{aligned} \tag{10}$$

Using (9) and (10), we can get

$$\begin{aligned} y^*[(k+d) \mid k] = \frac{G(z^{-1})}{C(z^{-1})} y(k) \\ + \frac{B(z^{-1})F(z^{-1})}{C(z^{-1})} u(k) \end{aligned} \tag{11}$$

In a digital system, the PID controller algorithm with digital filter is commonly used. So (5) can be written as

$$u(z^{-1}) = \frac{r_0 + r_1 z^{-1} + r_2 z^{-2}}{(1 - z^{-1})(1 + s_1 z^{-1})} e(z^{-1}) \tag{12}$$

So the controller is designed according to the discrete PID controller (12).

$$\{y_r - y^*[(k+d) \mid k]\} R(z^{-1}) = S(z^{-1}) u(k) \tag{13}$$

where,

$$\begin{aligned} S(z^{-1}) &= (1 - z^{-1})(1 + s_1 z^{-1}) \\ R(z^{-1}) &= r_0 + r_1 z^{-1} + r_2 z^{-2} \end{aligned}$$

Using (6), (9), (11), (13), the pole assignment optimal prediction self-tuning control system output can be written as

$$\begin{aligned} y(k) = \frac{z^{-d} B(z^{-1}) R(z^{-1})}{S(z^{-1})A(z^{-1}) + B(z^{-1})R(z^{-1})} y_r(k) \\ + \frac{R(z^{-1})F(z^{-1})B(z^{-1}) + S(z^{-1})C(z^{-1})}{S(z^{-1})A(z^{-1}) + B(z^{-1})R(z^{-1})} e(k) \end{aligned} \tag{14}$$

From (14), the closed-loop system characteristic equation is

$$S(z^{-1})A(z^{-1}) + B(z^{-1})R(z^{-1}) = C(z^{-1})T(z^{-1}) \tag{15}$$

$T(z^{-1})$ is the expected characteristic polynomial assignment.

$$\begin{gathered} T(z^{-1}) = 1 + t_1 z^{-1} + t_2 z^{-2} + \cdots t_m z^{-m} \\ (m \le n+2) \end{gathered} \tag{16}$$

From (15), we can see that there are no lags in closed–loop system characteristic equation. So the pole assignment optimal prediction self-tuning PID control system can overcome long-time delay.

Solve (15), and then we can get the parameters of PID controller.

From the above, the pole assignment optimal prediction self-tuning algorithm is composed of system parameter identification and pole assignment optimal prediction algorithm. The steps can be summarized as follows

- Set the initial value; include model initial parameter θ and identification coefficient ρ and P etc.
- Sampling the current controlled quantity $u(k)$ and output quantity $y(k)$.
- Identify the model parameter $A(z^{-1})$ and $B(z^{-1})$.
- Using (3), $F(z^{-1})$ and $G(z^{-1})$ can be calculated.
- Using (6), the expected output $y^*[(k+d) \mid k]$ can be calculated.
- The controller parameter $S(z^{-1})$ and $R(z^{-1})$ can be calculated by using (12).
- Using (10), the controlled quantity $u(k)$ can be obtained.
- $u(k)$ substituted into equation (1), $y(k)$ can be obtained.
- Return to the second step.

V. TEMPERATURE CONTROL SYSTEM OF POWER STATION BOILER SUPERHEATED STEAM

The main steam temperature control of the power station boiler is one of the important parameters which will concern unit safety and economic operation. Commonly control methods are double-loop control system using differential compensation signal and cascade control system using the conventional PID controller. But the controlled object has characteristics of great inertia and long-time delay. For these control methods it is difficult to achieve the best control effect. The actual situation shows that although some power station have adopted Distributed Control System (DCS), the control quality of steam temperature is still not very ideal. The steam temperature will deviate from the set value above more than 8℃ even when the load changes with only 2%MCR/min rate for some power stations. So often the main steam temperature is often controlled by manual operation. It lead to the steady state temperature range expanded to the scope of ±6℃, this will reduce the economic operation of the unit and increase labor intensity of operator.

A. The Model of Superheated Steam Object

This passage is based on the superheated steam system of Anhui power station #2 boiler (600MW subcritical boiler). The main control system of steam temperature adopts cascade control system. The outer loop uses PID controller, and the inner loop uses P controller. The structure is shown in Fig. 1. γ_{t1} and γ_{t2} is the temperature transmitter slope coefficient. t_1 is the outlet temperature of desuperheater. t_2 is the outlet temperature of superheater. The controlled object is composed of spray water adjusting valve, desuperheater and superheater. The degree of opening of the spray water adjusting valve is the input signal of the control system, and the outlet temperature t_2 of the superheater is the output signal.

The controlled object consists of two parts.

- With the opening degree of the spray water adjusting valve as input signal, the desuperheater outlet temperature t_1 as output signal, this part is called leading segment.
- With the outlet temperature t_1 of desuperheater as the input signal, the outlet temperature t_2 of superheater as output signal. This part is called inert segment.

The boiler superheater steam temperature identification model with a load of 550MW is given in reference [16]. In which we choose the model of desuperheater A, forward screen, and backward screen as an example. The transfer function of primary desuperheater A is $\frac{0.270}{(1+26.19S)}e^{-15S}$. The transfer function of forward screen A is $\frac{0.482}{(1+27.74S)(1+28.65S)}e^{-37S}$. The transfer function of backward screen is $\frac{0.576}{(1+155.59S)}e^{-46S}$. The parameter of inner PID K_P is 50. Thus we can get the main loop model $\frac{3.75}{(1+26.19S)(1+27.74S)(1+28.65S)(1+155.59S)}e^{-98S}$.

This passage will use the superheated steam temperature model as the simulation research object. Superheater steam temperature control scheme in the paper adopts the cascade control system which combined outer master PID with pole assignment optimal prediction algorithm, it don't change the inner loop characteristics of the traditional cascade PID control system. The generalized controlled object model is as shown in Fig. 2.

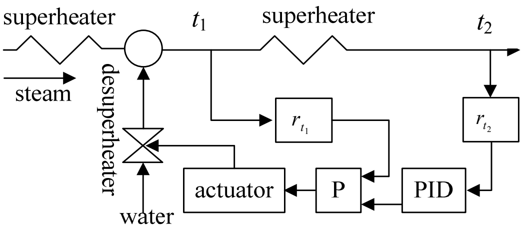

Fig. 1. Steam temperature cascade control system.

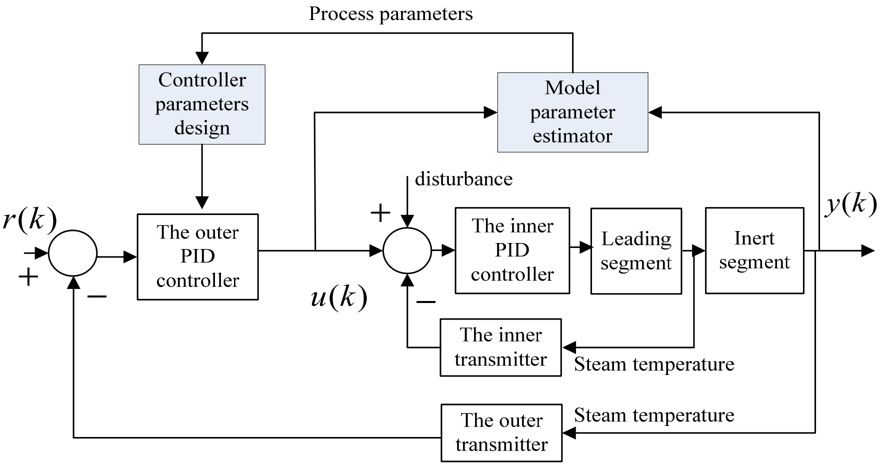

Fig. 2. The structure of superheated steam temperature cascade system.

B. The Algorithm Flow Based Pole Assignment Optimal Prediction

The algorithm flow based pole assignment optimal prediction is shown in Fig. 3.

C. Simulation Study

In order to facilitate simulation, take the combination of the feedback close loop of leading segment and inert segment as the generalized object, and adopt a sub-optimal reduction method [17] with time delay system to simplify the generalized object. At the last we get the equivalent approximate model (typical first-order inertia object with pure time delay)

$$G = \frac{3.75}{170.5S+1}e^{-170S}$$

The parameters of discrete model to be identified are

$$a_1 = -0.39,\ b_0 = 2.28.$$

According to the viewpoint of pole placement, take the second-order system closed loop transfer function standard form $G_n(s) = \frac{\omega_n^2}{(s^2+2\xi\omega_n s+\omega_n^2)}$ as the target. So the discrete characteristic polynomial is $T(z^{-1}) = 1-2e^{-\xi\omega_n T}\cos\omega_n T\sqrt{1-\xi^2}z^{-1}+e^{-2\xi\omega_n T}z^{-2}$, ω_n is undamped natural oscillation frequency, ξ is damping ratio.

When $\xi = 0.707$, it is the optimal dynamic second-order response model. The principle of choosing polynomial $C(z^{-1})$ is based on reference [16]. The shock which is caused by mutations in the input side should be avoided.

Then we choose $C(z^{-1}) = 1 + 0.5z^{-1} + 0.1z^{-2}$.

The initial simulation parameters settings, the forgetting factor $\rho = 0.95$ the estimation error covariance matrix $P = 10^6 I_2$ initial model parameters $\theta = [a_1 \quad b_0]^T = [0.001 \quad 0.001]^T$.

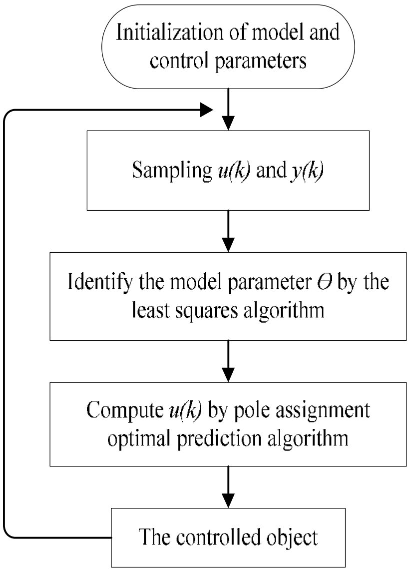

Fig. 3. The algorithm flow chart of pole assignment optimal prediction.

The simulation results are shown below:

- Fig. 4 is the simulation result of the object parameter identification process. We can see that at the beginning of the identification process, the result is not accurate. After a period of time identification, the parameters of the object stabilized gradually. So we can get the accurate model parameters.

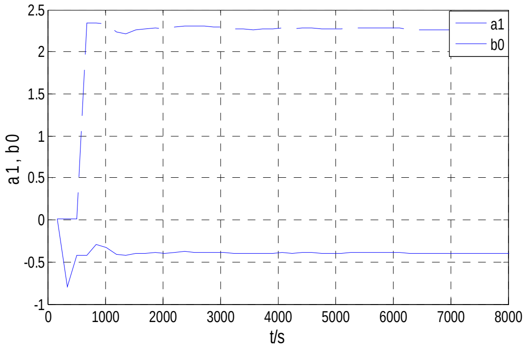

Fig. 4. Model parameters identification simulation.

- Under the ideal conditions, the simulation curve of the boiler superheater with pole assignment optimal prediction algorithm is as shown in Fig. 5. We can see that the system has good response characteristics, such as fast adjustment speed, good following feature to input signal, effective in suppression of overshoot.
- From Fig. 6, curve 1 is the simulation result of adopting pole assignment optimal prediction algorithm. Curve 2 is the simulation result of adopting conventional PID. We can see that the rise time of curve 1 is less than the rise time of curve 2. There is almost no overshoot in curve1. But for curve 2, there is about 8% overshoot. Therefore, the pole assignment optimal prediction self-tuning PID controller has better dynamic and static characteristic than conventional PID controller.

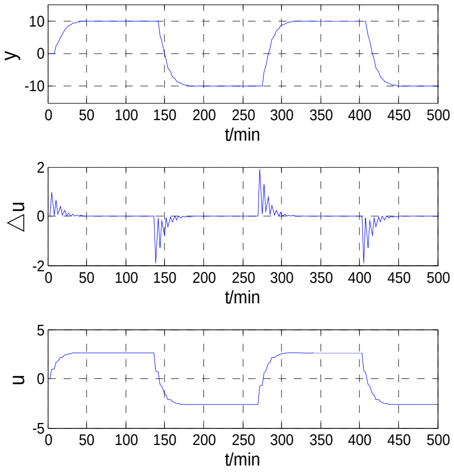

Fig. 5. The simulation.

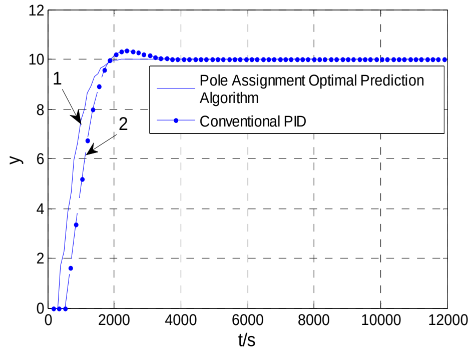

Fig. 6. The comparison of simulation curves.

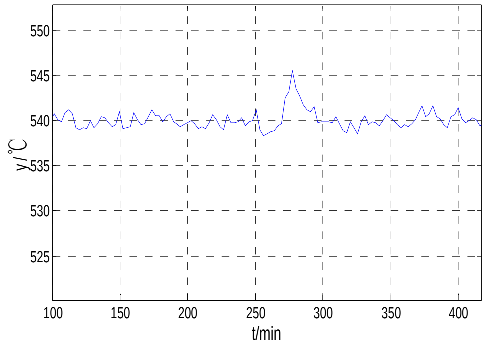

Fig. 7. Steady-state and dynamic simulation result of pole assignment optimal prediction algorithm.

- Fig. 7 is the curve of simulating the actual boiler. On 260 minutes, 10% disturbance was added to the system load, we can see that the output temperature deviates from the set value at 5℃, and then return to the set temperature value about 540℃ again. The result meet the actual production control requirement that the superheated steam temperature fluctuation range in dynamic situation is about ±6℃, at steady-state condition is about ±2℃.
- Fig. 8 is the simulation curve of adopting conventional PID controller. When disturbance was added to the system load, the output temperature deviates from the set value at 9 ℃, and then return to the set temperature value about 540 ℃. At steady-state condition, the superheated steam temperature fluctuation range is

about ±4℃.The control effect of adopting conventional PID controller is not ideal.

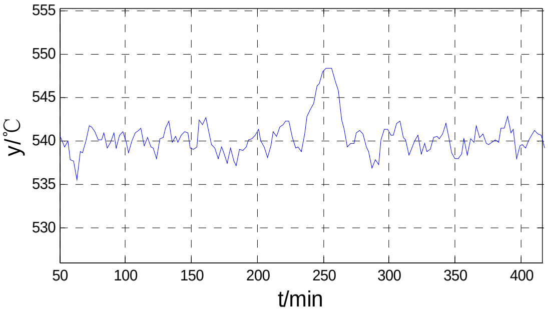

Fig. 8. Steady-state and dynamic simulation result of convention PID controller.

VI. CONCLUSION

With more and more power boiler units develop to high capacity, multiple parameters, and high efficiency, the production system became increasingly complex. System coupling, time-variation, nonlinear become more prominent. The superheated temperature of the steam superheater is a typical control object of nonlinear, long-delay, and great inertia. Although there are many new control methods for power steam temperature, the PID algorithm is still widely used because of its simple control structure and algorithm, easy to implement, and good applicability. In this paper, the PID controller parameter tuning method based on pole assignment optimal prediction algorithm is proposed. The model of superheated steam temperature is also simulated in this passage. The result of simulation verifies the effectiveness of the pole assignment optimal prediction algorithm.

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