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Stabilization of Boiler Steam Temperature using DSC Approach

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Abstract. A novel steam temperature control method is developed using the dynamic surface control method in this paper which is based on the saturated water-steam temperature system states observer and the one-order dynamics of the experiment for sprayer element. The proposed control method is effective in compensating for the disturbance of load and fuel. Simulation results show that the dynamic surface control method still ensures an accurate result, even if the loads change in a great and parameters of the controlled plant change significantly.

Keywords: steam temperature; dynamic surface control; third-order dynamics

1 Introduction

The continuous process in the heat exchanger is a complex system characterized by nonlinearity, uncertainty and load disturbance. The steam generating from water by burning fuel is used to generate electricity in one or more turbines. The control of steam temperature is critical in operations of utility boilers .It is important that the temperature of steam existing from a boiler and entering a steam turbine is at an optimally desired value .If the steam temperature is too high ,it may cause damage to the blades of the steam turbine for various metallurgical reasons. If the steam temperature is too low, it may contain water particles which may cause damage to components of the steam turbine. Typically, a boiler contains cascaded heat exchanger sections where the steam existing from one heat exchanger section with the temperature increasing at each heat exchanger section until the steam is output to the turbine at the desired steam temperature. In such systems, the control of the steam is often achieved by spraying saturated water in to the steam at a point before the final heat exchanger section.

The main steam temperature control system is necessary to ensure high efficiency and high load-following capability in the operation of modern power plant, which has the characteristics of large inertia, large time-delay and time-varying, etc. Thus conventional PID control strategy cannot achieve good control performance. Presently, engineers and technicians adopt some new control methods , such as advanced PID algorithms ,Fuzzy control methods, neural net work and etc. to solve

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the steam temperature control problems. A nonlinear long range predictive controller based on neural networks is developed to control the main steam temperature by Liu[1];A generalized predictive control was proposed to control the steam temperature in the paper[2];A composite control strategy based on variable universe fuzzy logic control integrated with immune and self-tuning PID control is presented in the paper[3],It has stronger robustness and better self-adaptive ability, which can be adaptive to the change in the parameters of the controlled plant.

In this paper ,a novel controller is design with dynamic surface method for the system of spraying water-steam temperature. In this system ,controlled variable is steam temperature of super-heater exit ,control variable is the saturated water. Firstly, two-order dynamic surface method needs three variable, and the global state observer is constructed for the application. Secondly, temperature controller is designed adopting dynamic surface control method, avoiding the occurrence of high-order derivatives of the spraying water in the expression of the control law.

1.1 Description of the system

The sprayer and superheater steam generation process is illustrated in Fig. **1**,and the control signal from controller to change the electrical valve ,and the volume flow is changed into steam ,the goal of control is to make the steam temperature fluctuate at the desired value under the condition with any power unit load.

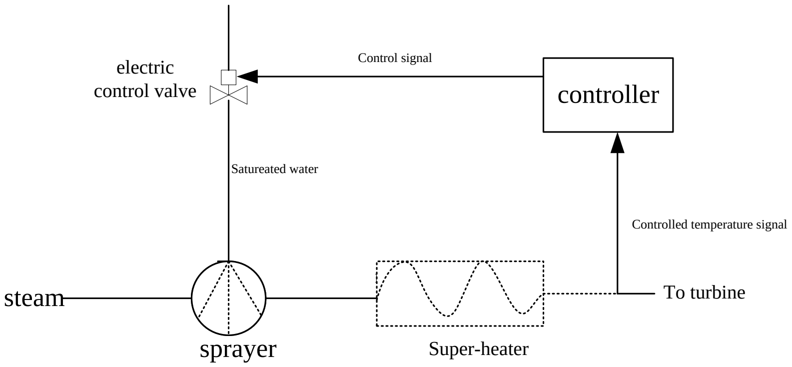

Fig. 1.control system structure

The mathematical model of saturated water-steam temperature transfer function is given in Eq.(1), where Y is steam temperature, X is volume flow of saturated water from sprayer to steam. In the transfer function P is steam mass flow related to load , $c_P, \tau_0, T_m, \alpha_D$ are parameters related to structure of components invariantly .In practice ,there parameters have obviously effect on the characteristic of the process .

$$W_G = \frac{Y}{X} = \frac{k}{P\, c_p (1 + 0.5(\tau_0 + T_m\, \alpha_D\, s)} \tag{1}$$

The former mathematic model was built neglecting the dynamic of the valve of sprayer, so this paper rebuilds the mathematic model of saturated water-steam temperature with the respect to the dynamic of the valve .The transfer function simple is given by fitting lab data that can be expressed as follows:

$$W = \frac{K}{(1 + T_0\, S)^3} \tag{2}$$

To simplify the design process using dynamic surface method, It is transferred into state equations in Eq. (3) :

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \tag{3}$$

Where

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}; A = \begin{bmatrix} -\frac{1}{T_0} & \frac{1}{T_0} & 0 \\ 0 & -\frac{1}{T_0} & \frac{1}{T_0} \\ 0 & 0 & -\frac{1}{T_0} \end{bmatrix}; B = \begin{bmatrix} 0 \\ 0 \\ K_0 / T_0 \end{bmatrix}; C = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \tag{4}$$

Parameters in equation (3) are substituted by $a = 1/T_0$, $b = K_0 / T_0$;State variables are defined as $[x_1 \quad x_2 \quad x_3]^T$,The Eq.(2) is written in the form of

$$\begin{cases} \dot{x}_1 = ax_2 - ax_1 \\ \dot{x}_2 = ax_3 - ax_2 , y = x_1 , \\ \dot{x}_3 = bu - ax_3 \end{cases} \tag{5}$$

Output $y = x_1$ is the steam temperature, x_2 and x_3 have no obvious physical meaning that are got by state prediction ,and control input is the control signal to sprayer deciding amount of saturated waters praying into the steam. The goal of control is to design a dynamic surface controller to make the steam temperature tracking the desired value x_{1d} quickly in economy.

1.2 State observer

In the Eq.(3), x_1 is the steam temperature that is measured by three sets of thermocouples .while state variable x_2 and x_3 are not physical quantity, it impossible to get the values of state variable x_2 and x_3, using common measurement instrument and methods. For completing the dynamic surface controller design, we construct state observer and get the value that have no obvious physical meaning by state prediction.

Pole - placement technique is employed to integrate the states, choose parameter $K = [K_1 \quad K_2 \quad K_3]^T$, define $A_0 = A - KC$,where A_0 satisfy Hurwitz polynomial. The state-space observer is designed as follows:

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + Bu + K(\mathrm{y} - \hat{\mathrm{y}}) \\ \hat{\mathrm{y}} = C\hat{x} \end{cases} \tag{6}$$

Where $\tilde{x}$ is observation error of state vector,

$$\tilde{x} = x - \hat{x} \tag{7}$$

Then derivate the Eq.(7), we get Eq.(8)

$$\dot{\tilde{x}} = \dot{x} - \dot{\hat{x}} = A_0\tilde{x} \tag{8}$$

Because A_0 satisfy Hurwitz matrix, $\tilde{x}$ is decaying exponentially to 0,and the inequality $\dot{\tilde{x}}_i^2 \le \dot{\tilde{x}}_i^2(0)$ is satisfied. The Eq.(6) is written in components as follows:

$$\begin{cases} \dot{\hat{x}}_1 = a\hat{x}_2 - a\hat{x}_1 + K_1(x_1 - \hat{x}_1) \\ \dot{\hat{x}}_2 = a\hat{x}_3 - a\hat{x}_2 + K_2(x_1 - \hat{x}_1) \\ \dot{\hat{x}}_3 = bu - a\hat{x}_3 + K_3(x_1 - \hat{x}_1) \end{cases} \tag{9}$$

2 Design of dynamic surface controller

The dynamic surface control method proposed by Swaroop [12] was able to resolve the “explosion of terms” problem, which is caused by differential coefficient calculation in the model, and the problem can bring a complexity that will cause the usually method hardly to be applied to the practical applications, especially to the design of control law considering one-order dynamics of actuators for super heater steam system .

In practical applications, the temperature control accuracy and the rapidity are not easy to obtain simultaneously, but their bounds can be known a priori. Using dynamic surface control method, controller is designed as follows.

In order to make the stability of control system avoid the limit by the main steam flow P, the P is added to the definition of first error-surface.

Step 1) Design a virtual control law for x_2 .

The first error-surface is defined as

$$S_1 = P(x_1 - x_{1d}) \tag{10}$$

x_{1d} is desired value and Eq. (10)its derivative is

$$\dot{S}_1 = -(\dot{P} + Pa)x_1 - \dot{P}x_{1d} - P\dot{x}_{1d} + Pa(\hat{x}_2 + \tilde{x}_2) \tag{11}$$

Choose a virtual control $\bar{x}_2$ to drive $S_1 \to 0$ as follows:

$$\bar{x}_2 = \frac{1}{Pa}(C_1 S_1 + (\dot{P} + Pa)x_1 + \dot{P}x_{1d} + P\dot{x}_{1d}) \tag{12}$$

where x_{1d} is the desired value, C_1 is positive constant. Then, to obtain the filtering virtual control x_{2d} , pass $\bar{x}_2$ through a first-order filter with time constant $\tau_2 > 0$ as follows:

$$\tau_2 \dot{x}_{2d} + x_{2d} = \bar{x}_2 \qquad x_{2d}(0) = \bar{x}_2(0) \tag{13}$$

Step 2) Design a virtual control law for x_3 .

Define the second error-surface as

$$S_2 = \hat{x}_2 - x_{2d} \tag{14}$$

And derivate Eq.(14), its derivative is

$$\dot{S}_2 = \dot{\hat{x}}_2 - \dot{x}_{2d} = a\hat{x}_3 - a\hat{x}_2 + C_2(x_1 - \hat{x}_1) - \dot{x}_{2d} \tag{15}$$

Choose a virtual control $\bar{x}_3$ to drive $S_2 \to 0$ as follows:

$$\bar{x}_3 = \frac{1}{a}(C_2 S_2 + a\hat{x}_2 - C_2(x_1 - \hat{x}_1) + \dot{x}_{2d}) \tag{16}$$

where C_2 is a positive constant. Then, to obtain the filtering virtual control x_{3d} , pass $\bar{x}_3$ through a first-order filter with time constant $\tau_3 > 0$ as follows:

$$\tau_3 \dot{x}_{3d} + x_{3d} = \bar{x}_3 \qquad x_{3d}(0) = \bar{x}_3(0) \tag{17}$$

Step 3) Design the actual control u

Define the third error-surface as

$$S_3 = \hat{x}_3 - x_{3d} \tag{18}$$

and its derivative is

$$\dot{S}_3 = bu - a\hat{x}_3 + K_3(x_1 - \hat{x}_1) - \dot{x}_{3d} \tag{19}$$

Choose an actual control u to drive $S_3 \to 0$ as follows:

$$\dot{S}_3 = -C_3 S_3 \tag{20}$$

The control is achieved as followings: using Eq.(19) and Eq.(20), we get Eq.(21)

$$\begin{aligned} -C_3 S_3 &= bu - a\hat{x}_3 + K_3(x_1 - \hat{x}_1) - \dot{x}_{3d} \\ -C_3(\hat{x}_3 - x_{3d}) &= bu - a\hat{x}_3 + K_3(x_1 - \hat{x}_1) - \dot{x}_{3d} \\ bu &= (-C_3 + a)\hat{x}_3 + C_3 x_{3d} + a\hat{x}_3 - K_3(x_1 - \hat{x}_1) + \dot{x}_{3d} \end{aligned} \tag{21}$$

Substitute parameters by Eq.(17) and (18), and Eq.(22) is obtained

$$\begin{aligned} bu &= (-C_3 + a)\hat{x}_3 + C_3 x_{3d} + a\hat{x}_3 - K_3(x_1 - \hat{x}_1) + \frac{\overline{x}_3 - x_{3d}}{\tau_3} \\ \overline{x}_3 &= \frac{1}{a}(C_2 S_2 + a\hat{x}_2 - K_2(x_1 - \hat{x}_1) + \dot{x}_{2d}) \\ bu &= (-C_3 + 2a)\hat{x}_3 + (C_3 - \frac{1}{\tau_3})x_{3d} - K_3(x_1 - \hat{x}_1) + \frac{1}{a\tau_3}(C_2 S_2 + a\hat{x}_2 - K_2(x_1 - \hat{x}_1) + \dot{x}_{2d}) \end{aligned} \tag{22}$$

Deal the equations repeatedly, and Eq.(23) is obtained

$$\begin{aligned} bu = [&(C_3 - a)\hat{x}_3 + (C_3 - \frac{1}{\tau_3})x_{3d} + (a + \frac{C_2}{a\tau_3})\hat{x}_2 - (\frac{C_2}{a\tau_3} + \frac{C_2}{a\tau_3\tau_2})x_{2d} + \frac{C_2}{a^2\tau_3\tau_2}(C_1 + 1 + a)x_1 + \\ &\frac{C_2}{Pa^2\tau_3\tau_2}(\dot{P} - C_1 P)x_{1d} + \frac{C_2}{a^2\tau_3\tau_2}\dot{x}_{1d}] \end{aligned} \tag{23}$$

Completing above work, we get the control function to satisfy the requirement expressed in Eq.(24)

$$u = \frac{1}{b}\left[\begin{array}{l} (C_3 - a)\hat{x}_3 + (C_3 - \frac{1}{\tau_3})x_{3d} + (a + \frac{C_2}{a\tau_3})\hat{x}_2 - (\frac{C_2}{a\tau_3} + \frac{C_2}{a\tau_3\tau_2})x_{2d} + \\ \frac{C_2}{a^2\tau_3\tau_2}(C_1 + 1 + a)x_1 + \frac{C_2}{Pa^2\tau_3\tau_2}(\dot{P} - C_1 P)x_{1d} + \frac{C_2}{a^2\tau_3\tau_2}\dot{x}_{1d} \end{array}\right] \tag{24}$$

In fact, it is hard to estimate the flow disturbance and load uncertainties, so function sgn(.) are used to deal with system components uncertainties, then a practical new control law considering system uncertainties is given in Eq.(25) as follows:

$$u = \frac{1}{b}\left[\begin{array}{l} (C_3 - a)\hat{x}_3 + (C_3 - \frac{1}{\tau_3})x_{3d} + (a + \frac{C_2}{a\tau_3})\hat{x}_2 - (\frac{C_2}{a\tau_3} + \frac{C_2}{a\tau_3\tau_2})x_{2d} + \\ \frac{C_2}{a^2\tau_3\tau_2}(C_1 + 1 + a)x_1 + \frac{C_2}{Pa^2\tau_3\tau_2}(\dot{P} - C_1 P)x_{1d} + \frac{C_2}{a^2\tau_3\tau_2}\dot{x}_{1d} + \frac{\varepsilon_1 \operatorname{sgn} x_1}{\tau_3\tau_2} \end{array}\right] \tag{25}$$

3 Conclusion

In this paper, the new control method accounting for dynamics of first order actuator is designed using dynamic surface control method. The new control method need to know the state space of the continuous process , and the state observer is constructed based on pole-placement method for that . So this is a practical control method overcoming the bad effect causing by first-order dynamics of sprayer valve.

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