Application of Improved Model-Free Adaptive Control in an Industrial Boiler System

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Abstract: For a utility boiler to achieve good performance, dynamic variables such as drum level, steam temperature, water level of the drum, and others must be controlled. Based on operating requirements and the analysis of the characteristics of an industrial boiler, a complete control scheme for a boiler should be designed. Specifically, due to the typical nonlinear and coupled characteristics of the outlet pressure of a boiler, an improved model-free adaptive control (IMFAC) method is used to maintain it at the appropriate values. The automatic control system is realized using the DCS of SIMATIC PCS 7 Box. Detailed comparisons between IMFAC and the traditional PID control demonstrate the practicability and robustness of the IMFAC control scheme.

Key Words: Boiler system; Improved model-free adaptive control; PCS 7 BOX

1 Introduction

A boiler unit, which produces superheated steam, is widely used in power generation, in chemical plants, and in daily life. It constantly works under high pressure and temperature, so its security is very important. Further, all the quantity indexes of a boiler such as steam pressure, temperature, and water level of the drum affect the performance of plant operation, so these must be maintained at their appropriate values. However, the physical constraints exerted on the actuators must be satisfied by the control signals. These constraints can be the magnitude and saturation rate for the control valves of the fuel, steam, and feed-water flow [1, 2].

An industrial boiler unit is a nonlinear complex system. Several dynamic models of the boiler system have been developed [3–5], and various control methods have been applied to the boiler controller design in previous works (e.g., adaptive control [6], Linear Quadratic Gaussian [7], predictive control [8], robust control [9], and intelligent control [10, 11]). However, accurate modeling is inevitable. In fact, the boiler system is nonlinear, coupled, and uncertain, and its accurate model is hardly available in practice. Hence, a simple and robust control method—a model-free adaptive control (MFAC) that is insensitive to modeling uncertainties and is suitable for nonlinear dynamics—is considered in this paper. Recently, Hou [12] developed a new dynamic linearization method by introducing the concept of pseudo-partial derivative; the MFAC scheme based on pseudo-partial derivative was then proposed for general nonlinear systems. As a data-driven method in nature, it has received increasing attention from researchers in the control field [13, 14].

The boiler system involves a complex process with multiple variables, strong coupling, strong interference, and a large lag. Due to the influences of these factors, the traditional PID control effect is not ideal [15]. Based on operating requirements and the analysis of the characteristics of an industrial boiler, a complete control scheme for a boiler should be designed, which includes the combustion control system, drum control system, stem temperature, and other control systems. In particular, for the boiler unit to achieve good performance, the improved model-free adaptive control strategy (IMFAC) is proposed to control the superheated pressure steam in which the fuel flow is the manipulated variable. Detailed comparisons between IMFAC and the traditional PID control prove that the IMFAC control scheme is more practical and robust.

2 Technological of the industrial boiler

The process involved in the natural circulation boiler is shown in Fig. 1. The feed water flow of the boiler is F1101, and the bypass valve is HV1101. The boiler feed water is divided into two channels. One flows into the desuperheater E1101 for preheating. After preheating, the boiler feed water mixes with the other channel and flows into economizer E1102. Two feed water pipes have their respective control valves: V1102 and V1103.

The drum pressure is P1103, and there is a level detection T1102 in the middle of the drum. In the drum, saturated steam with temperature T1102 is obtained by gas-liquid separation. T1103 is the superheated steam temperature, which has passed the furnace. The role of the desuperheater is to adjust the superheated steam. The pressure, temperature, and flow of the end-point superheated steam are P1104, T1104, and F1105, respectively. V1105 is a control valve in the outlet pipe.

Fuel is fed into the burner of furnace F1101 through fuel pump P1102 with flow rate F1103 and pressure P1101. The control valve V1104 is located in the fuel pipeline. Air is fed into the burner at flow rate F1104 through the frequency conversion fan K1101. The frequency of the converter is S1101 (normalized from 0% to 100%).

The fuel gas flow and temperature in the outlet of the economizer are F1107 and T1105, respectively. There are online analysis instruments to measure the oxygen content of fuel gases. DO1101 is the damper in the economizer (fuel gas) outlet.

* This work is supported by National Science Foundation of China under Grant No. 61174128, 60974031, and the Fundamental Research Funds for the Central Universities, China (No. ZZ1223).
The furnace temperature T1101 is extremely high, which is measured by an infrared non-contact sensor so that it can only provide a general reference. The furnace draft is P1102, which is an important parameter [16].

![Fig.1. The technology of the industrial boiler](image)

The nominal operating conditions are as follows:

**Table 1: Summary of the basic process control for the boiler**

<table>
<thead>
<tr>
<th>No.</th>
<th>Control loop</th>
<th>Controlled variable</th>
<th>Manipulated variable</th>
<th>Control action</th>
<th>Control law</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Drum-water level control loop</td>
<td>Drum-water level</td>
<td>Feed water flow</td>
<td>positive</td>
<td>PI</td>
</tr>
<tr>
<td>2</td>
<td>Feed water flow control loop</td>
<td>Feed water flow</td>
<td>Feed water flow</td>
<td>positive</td>
<td>PI</td>
</tr>
<tr>
<td>3</td>
<td>Fuel quantity control loop</td>
<td>Fuel quantity</td>
<td>Fuel quantity</td>
<td>positive</td>
<td>PI</td>
</tr>
<tr>
<td>4</td>
<td>Air quantity control loop</td>
<td>Air quantity</td>
<td>Air quantity</td>
<td>positive</td>
<td>PI</td>
</tr>
<tr>
<td>5</td>
<td>Superheated steam pressure control loop</td>
<td>Superheated steam pressure</td>
<td>Fuel quantity &amp; Air quantity</td>
<td>positive</td>
<td>IMFAC</td>
</tr>
<tr>
<td>6</td>
<td>Fuel gas oxygen content control loop</td>
<td>Fuel gas oxygen content</td>
<td>Air quantity</td>
<td>positive</td>
<td>PI</td>
</tr>
<tr>
<td>7</td>
<td>Superheated steam temperature split control loop</td>
<td>Superheated steam temperature</td>
<td>Attemperator cold water</td>
<td>negative</td>
<td>PI</td>
</tr>
<tr>
<td>8</td>
<td>Furnace draft control loop</td>
<td>Furnace draft</td>
<td>Fuel gas flow</td>
<td>negative</td>
<td>PI</td>
</tr>
<tr>
<td>9</td>
<td>Superheated steam flow control loop</td>
<td>Steam flow</td>
<td>Steam flow</td>
<td>positive</td>
<td>PI</td>
</tr>
</tbody>
</table>

4 Superheated steam pressure control based on IMFAC

4.1 Principles of MFAC

The superheated steam needed downstream usually goes through the convection and radiation section of the boiler. Therefore, the superheated steam control system used by fuel flow obviously involves a huge lag, and the traditional PID control effect is not ideal. In this paper, the MFAC controller is selected to control the superheated steam, which is composed of the “pan-model” and the “control function.” Notably, the pan-model does not depend on the concrete mathematical model of the controlled object. The nature of MFAC involves refining the pan-model when it is controlled, which can improve controller performance [18]. A general discrete time nonlinear system is given as follows:

\[ y(k+1) = f(y(k), \ldots, y(k-m), u(k), \ldots, u(k-n)) \]  \hspace{1cm} (1)

where \( y(k) \) and \( u(k) \) are the system input and output, respectively, and \( n \) and \( m \) are the system dimensions. According to the system dynamic input, its pan-model is defined as follows:

\[ y(k) \approx y(k-1) = \phi(k-1)[u(k-1) - u(k-2)] \]  \hspace{1cm} (2)

where \( \phi(k-1) \) can be estimated by every estimation algorithm of the time-varying parameter. The criterion function of parameter estimation is proposed as follows:

\[ J_0(\phi(k)) = (y(k) - y(k-1) - \phi(k) \Delta u(k-1))^2 + \mu_0 (\hat y(k) - \phi(k-1))^2 \]  \hspace{1cm} (3)

where \( y(k) \) is the \( k \)-th output value, and \( \mu_0 \) is the weight factor.

To obtain the pseudo-partial-derivative \( \hat \phi(k-1) \), the gradient descent-optimizing technique is used for the cost function Eq. (2), then

\[ \hat \phi(k) = \hat \phi(k-1) \]

\[ + \eta \Delta u(k-1) |\Delta y(k-1) - \hat \phi(k-1) \Delta u(k-1)|/|\mu_0 + |\Delta u(k-1)|^2 \]  \hspace{1cm} (4)

where \( \eta \) is optimal step, and the following is set:

\[ \hat \phi(k) = \hat \phi(1) \text{ if } \hat \phi(k) \leq \varepsilon (\varepsilon > 0) \text{ or } |\Delta u(k-1)| \leq \varepsilon \]  \hspace{1cm} (5)
An expanded integrated square error index is proposed by considering set-point tracking, noise restraining, and constraint of the control signal in practical applications, as shown in the following:

\[ J(u(k)) = [y^*(k+1) - y(k+1)]^2 + \lambda [u(k)-u(k-1)]^2 \]  

where \( \lambda \) is the weight factor. In this criterion function, the first part \([y^*(k+1) - y(k+1)]^2\) can reduce the steady tracking error, whereas the second part \([u(k)-u(k-1)]^2\) can restrict a great change in the control input.

The one-step-ahead control sequence can then be obtained using the gradient descent-optimizing technique for the cost function Eq. (6):

\[ u(k) = u(k-1) + \rho \hat{\phi}(k) [y^*(k+1) - y(k)]/\hat{\mu} \]  

(7)

where \(\rho (0<\rho<1)\) is the optimal step.

Evidently, the MFAC controller is composed of the pan-modeling identification algorithm (4) and a basic control algorithm (7). The block diagram of the MFAC method is shown in Fig. 2.

The improved MFAC algorithm consists of Eqs. (11-13) and the one-step-ahead control sequence can then be obtained using the gradient descent-optimizing technique for the cost function Eq. (6):

\[ \hat{\phi}(k) = \hat{\phi}(k-1) + \eta \hat{\Delta}u(k-\tau-1) \]

(10)

The one-step-ahead control sequence can be obtained:

\[ u(k) = u(k-1) + \rho \hat{\phi}(k) [y^*(k+1) - y(k)]/\hat{\mu} \]  

(11)

Using the parameter estimation method similar to MFAC, the following is derived:

\[ \hat{\phi}(k) = \hat{\phi}(k-\tau-1) + \eta \Delta u(k-\tau-1) \]

(12)

To obtain a stronger capability for time-varying parameter tracking, restart algorithm is used:

\[ \hat{\phi}(k) = \hat{\phi}(1) \text{ if } \hat{\phi}(k) \leq \epsilon (\epsilon > 0) \text{ or } \Delta u(k-\tau-1) \leq \epsilon \]

(13)

The improved MFAC algorithm consists of Eqs. (11-13) [20].

5 Implementation of the control system

The basic process control system is implemented in SIMATIC PCS 7 BOX. A brief explanation of the control implementation is given, with the combustion system and the fuel gas oxygen content control system as an example. It is the core part of the boiler control system.

The main loop of the combustion system is the superheated steam pressure controller, whereas the secondary loop is the fuel flow-air quantity controller. Using the structure control language provided by PCS 7 V6.1, an improved MFAC module is created based on the principles described in Section 4. The whole control scheme is realized by the continuous function chart (CFC) in which many basic modules are used, such as the analog input module (CH_AI), analog output module (CH_AO), MFAC module (FB1500), PID control module (CTRL_PID), adder module (ADD4_P), multiplier module (MUL4_P), and analog operation module (OP_A_LIM). The CFC of the combustion and fuel gas oxygen content control system can be created, as shown in Fig. 4.
After finishing preparation work, each control system is switched to automatic mode based on the no-disturbance switching requirement. Then all of the parameters of the boiler control system are adjusted. When the boiler is operated in normal condition, some disturbances are introduced into the boiler system, such as load changing. The control goal and the difficulties are that the superheated steam pressure and temperature should be kept within normal limits in the whole operation, so their dynamic responses are mainly discussed here.

6 Results analysis

According to the above operation, the control experiments include superheated steam pressure set-point changing, superheated steam temperature set-point changing, drum-water level set-point changing, feed water disturbance, and boiler load increase and decrease.

(1) Superheated steam pressure P1104 set-point changing

Under normal conditions, the superheated steam pressure set-point is changed from 3.8 to 3.6 mPa. The results of the IMFAC and PID controllers are shown in Fig. 5. The dynamic responses of P1104 set-point changing based on IMFAC controller are shown according to the time sequence in Fig. 5 (a). In this figure, the following variables are given: superheated steam flow (red), superheated steam pressure (yellow), furnace draft (green), superheated steam temperature (black), drum water level (orange), and fuel gas oxygen content (purple). The comparison between IMFAC and PID are shown in Fig.5 (b). In this figure, the following control methods are given: IMFAC (red), PID (blue). As can be seen, the response time in the IMFAC and PID controllers is 300 and 800 s, respectively. So the response speed of IMFAC is faster than that of the traditional PID controller.

(2) Superheated steam temperature T1104 set-point changing

In Fig. 6, the superheated steam temperature T1104 set-point changes between 450 and 430°C. First, when the set-point decreases from 450 to 430°C, the response time in the IMFAC and PID controllers is 300 and 400 s, respectively. When the set-point increases from 430 to 450°C, it is 150 and 180 s, respectively. Therefore, the response speed of IMFAC is faster than that of the traditional PID controller.
(3) Drum-water level L1102 set-point changing
Under normal boiler conditions, the drum water level L1102 set-point changes from 55% to 50%; the results of the IMFAC and PID controllers are shown in Fig. 7. The overshoot of P1104 (Superheated stem pressure) in the IMFAC and PID controllers is 1.21% and 2.0%, respectively. In the meantime, the overshoot of L1102 (Drum water level) is 0.964% and 1.012%. Thus the IMFAC control system responds more quickly. What is more important is that the disturbance effect to P1104 is inferior to that to the PID controller. Therefore, the IMFAC control strategy has better features such as fast response and strong anti-interference performance.

(4) Feed water disturbance
As shown in Fig. 8, the opening of feed water bypass valve HV1101 varies from 0% to 30%, and its duration time is 300 s. The control results are listed in Table 2. This indicates that the IMFAC controller can quickly respond in rejecting feed water disturbance, and superheated steam pressure P1104 restores stability after 120 s.

(5) Boiler load increase and decrease
Under normal conditions, the boiler load (superheated steam flow F1105) is increased from 11 to 16 kg/s (equivalent to 40–60 t/h); the control results are shown in Fig. 9 and Table 3. After this control system is stabilized, the boiler load begins to decrease from 16 to 13 kg/s (from 60 to 48 t/h); the results are shown in Fig. 10 and Table 4. When the boiler load changes (increase or decrease), superheated steam pressure P1104 and temperature T1104 are affected, but they are finally restored to the set point values 3.8 mPa and 450°C. The control process and the resulting for load decrease are not strictly the opposite of that for load increase, which means that the boiler is a typical nonlinear system. As shown in Fig. 9 and 10, the response time of load change (including increase and decrease) using the IMFAC and PID controllers is 4,000 and 5,800 s, respectively. Therefore, the IMFAC control strategy has better features than the PID controller, such as fast response and strong anti-interference performance.

Table 2 Results of the IMFAC and PID controller effects for bypass valve HV1101 opening

<table>
<thead>
<tr>
<th>Variable</th>
<th>Response index</th>
<th>IMFAC</th>
<th>PID</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1102</td>
<td>Response time (s)</td>
<td>340</td>
<td>380</td>
</tr>
<tr>
<td>L1102</td>
<td>Overshoot (%)</td>
<td>0.69</td>
<td>0.714</td>
</tr>
<tr>
<td>P1104</td>
<td>Overshoot (%)</td>
<td>0.237</td>
<td>0.342</td>
</tr>
</tbody>
</table>

Table 3 Results of the IMFAC and PID controller effects for load increase from 11 to 16 kg/s

<table>
<thead>
<tr>
<th>Variable</th>
<th>Response index</th>
<th>IMFAC</th>
<th>PID</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1104</td>
<td>Overshoot (%)</td>
<td>7.771</td>
<td>10.436</td>
</tr>
<tr>
<td>P1104</td>
<td>Rise time (s)</td>
<td>869</td>
<td>1232</td>
</tr>
<tr>
<td>P1104</td>
<td>Response time (s)</td>
<td>2500</td>
<td>3500</td>
</tr>
<tr>
<td>F1105</td>
<td>Initial value (Kg/s)</td>
<td>11.056</td>
<td>11.056</td>
</tr>
<tr>
<td>F1105</td>
<td>Overshoot (%)</td>
<td>4.887</td>
<td>7.509</td>
</tr>
<tr>
<td>F1105</td>
<td>Steady-state value (Kg/s)</td>
<td>16.029</td>
<td>16.106</td>
</tr>
<tr>
<td>T1104</td>
<td>Overshoot (%)</td>
<td>4.86</td>
<td>5.01</td>
</tr>
<tr>
<td>P1102</td>
<td>Response process</td>
<td>No effect</td>
<td>Minimal oscillation</td>
</tr>
<tr>
<td>L1102</td>
<td>Response process</td>
<td>No effect</td>
<td>No effect</td>
</tr>
<tr>
<td>A1101</td>
<td>Response process</td>
<td>No effect</td>
<td>No effect</td>
</tr>
</tbody>
</table>
and robustness. 

With the PID controller, it has several advantages such as its faster response speed, strong anti-interference capability, and accuracy. The basic process control system is implemented in the SIMATIC PCS 7 BOX. The results show that the IMFAC controller, a novel method for industrial control, is more suitable for boiler control with severe disturbances. The complete control scheme for the boiler is designed, which includes five parts: combustion and fuel gas oxygen content control system, drum-water level control system, furnace draft control system, and superheated steam flow control system. IMFAC is used to control the superheated steam temperature. The basic process control system is implemented in SIMATIC PCS 7 BOX. The results show that the IMFAC controller meets industrial control requirements. Compared with the PID controller, it has several advantages such as its faster response speed, strong anti-interference capability, and robustness.

### 7 Conclusion

This paper presents the practical applications of IMFAC in an industrial boiler system. Based on operating requirements and the analysis of the characteristics, a complete control scheme for the boiler is designed, which includes five parts: combustion and fuel gas oxygen content control system, drum-water level control system, superheated steam temperature control system, furnace draft control system, and superheated steam flow control system. IMFAC is used to control the superheated steam pressure. The basic process control system is implemented in SIMATIC PCS 7 BOX. The results show that the IMFAC controller meets industrial control requirements. Compared with the PID controller, it has several advantages such as its faster response speed, strong anti-interference capability, and robustness.

### References


