Design of Superheated Steam Temperature Control System Based on ADRC-PID for Ultra Supercritical Unit

Jintao Guo, Xin Jiang

School of energy and power engineering, Inner Mongolia University of Technology, Huhhot, China, taoabc78@163.com

Abstract

In operation process of ultra supercritical unit, the stability of the superheated steam temperature depends on the adjusting fuel water ratio correctly. In order to improve the speed and accuracy of fuel water ratio, in this paper the active disturbance rejection control technology was used in superheated steam temperature control system in ultra supercritical units, proposing that in the secondary superheated steam temperature control system, the main regulator used ADRC, and the secondary regulator used traditional PID to control, that's the design of ADRC-PID superheated steam temperature control system. The main regulator can control the superheated steam temperature within permitted changes, the secondary regulator can eliminate various disturbances rapidly and finely, adjust the outlet temperature of spray de-superheater, and control the superheated steam temperature in the allowable range. Finally, the experimental results show that, superheated steam temperature control system with ADRC has better load adaptability, stronger robustness and anti-interference ability, faster tracking velocity than with PID, thus the control quality of ADRC is significantly superior to the traditional PID.

Keywords: Ultra Supercritical, Superheated Steam Temperature, Fuel Water Ratio, Active Disturbance Rejection Control

1. Introduction

The ultra supercritical unit is a device widely used to improve the power efficiency, save energy and reduce environmental pollution. Its technology is the most matured for clean coal power generation[1,2]. Ultra supercritical unit has high generating efficiency and good reliability. At the same time, as thermal power plant's thermal efficiency increases with the increasing of main steam parameter, so to achieve energy saving and reduce environmental pollution, large scale of high efficiency new control strategies, which can improve energy utilization and reduce environmental pressure are used to control main steam temperature of ultra supercritical unit[3]. Since from the middle of the twentieth Century, many experts and scholars has been continuing proposing and applying new control methods based on the essence nature of ultra supercritical unit, and has gradually obtained certain achievements. In reference [4], Darko introduced the Smith control theory and design methods; in reference [5], Zhao Wenjie introduced the internal model control theory and internal model controller design method, and studied on main steam pressure simulation of the thermal power plant; in reference [6], Kocaarslan studied and designed the adaptive controller and applied it in ultra supercritical units. Active disturbance rejection controller, ADRC, created by researcher Han Jingqing, is a practical integrated nonlinear approach for control system[7]. It has good robustness and disturbance resistance, does not need any object's mathematical model, and provides a better control method for delay system of uncertain size. The design applies ADRC technology into main steam temperature control system of large ultra supercritical unit. And its control efficiency is superior to the PID's, indicating that ADRC has a brighter application prospect in steam temperature control system in ultra supercritical unit.
2. Active disturbance rejection controller

We hypothesize that there is an external disturbance of uncertain nonlinear objects as bellow:

\[ y^{(n)} = f(y, \dot{y}, \cdots, y^{(n-1)}, w(t)) + b(t)u(t) \]  

(1)

Here \( f, w, b \) are all uncertain functions, the ADRC structure of these objects is showed as bellow in Figure 1,

**Figure 1.** Block diagram for ADRC controller

In Figure 1, TD is tracking differentiator; NLC is nonlinear combination; ESO is extended state observer; \( v(t) \) is a given input signal; \( e(t) \) is error signal; \( u(t) \) is input signal of a controlled object; \( w(t) \) is interference signal; \( y(t) \) is output signal of the controlled object; \( z(t) \) is state estimation signal; I is a unit matrix, \( b_0 \) is the intermediate value of change.

TD is used to arrange the transient process and give its all-order derivatives. In reference [7], specific forms of the second and third order TD are derived from the speed switch system, the form of the third order TD is more complex than that of the second order TD. Obviously, in higher order situations, it will be quite difficult and tedious to design TD according to the optimal control theory. In engineering, it usually only need to create a satisfactory transition process, rather than the optimal one. Therefore, we can build TD according to the actual situation, and make its form simple and easy to realize. Here, the author draws on nonlinear control inverse system method in choice of desired dynamical equations, using the recommended methods in reference [8], and arrange the ADRC transition process as bellow:

\[ \Phi(s) = \left( \frac{\omega^2}{s^2 + 2\zeta\omega s + \omega^2} \right)^2 \left( \frac{a\omega(n-2)}{s + a\omega(n-2)} \right)^{-n-2} \]  

(2)

Here, The N representing for object's order, when \( a \geq 5 \), the step response in equation (2) is similar to its first factor's in second order link; value \( \zeta \) from 0 to 1; select \( \omega \) appropriately, according to the desired dynamic characteristics. Equation (2) has direct and simple relationship with the performance index of a project control system, when N takes different step number, the transition process will be calculated out by equation (2).

ESO is the extended state observer. Its function is to make its outputs respectively tracking each state variable of object(1). However, in equation \( z_{n+1} \rightarrow a(t) = f[y, \dot{y}, \cdots, y^{(n-1)}, w(t)] + [b(t) - b_0]u(t) \), contains object uncertainty and external disturbance information, which can be compensated, i.e.
This open loop transfer relationship from $u_i(t)$ to $y(t)$, it would be an integrator tandem type object, thereby realizing the nonlinear uncertain system feedback linearization. ESO is constructed based on tracking differentiator in the observer forms[9]:

$$
\begin{align*}
\dot{z}_1 &= z_2 - \beta_1 g_1(z_1 - y(t)) \\
\vdots \\
\dot{z}_n &= z_{n+1} - \beta_n g_n(z_1 - y(t)) + b_i u(t) \\
\dot{z}_{n+1} &= -\beta_{n+1} g_{n+1}(z_1 - y(t))
\end{align*}
$$

(4)

In the equation above, $b_0$ is an intermediate value within $b(t)$ variations, nonlinear functions as $g_1(z), \cdots, g_n(z)$ and $g_{n+1}(z)$ can be properly selected, one form of $g_i(z)$ is as bellow[9]:

$$g_i(z) = f_{al}(z, a_i, \delta) = \begin{cases} 
|z|^{a_i} \text{sign}(z), & |z| > \delta \\
\frac{z}{\delta^{a_i-1}}, & |z| \leq \delta
\end{cases} \quad \delta > 0
$$

(5)

NLC achieves the nonlinear combination of errors between arranging the transition process and object state variables, so as to realize the nonlinear state error feedback, and provides the required control volume of $n^{th}$ order integrator tandem type object, see as bellow:

$$u_0 = \gamma_1 g_1(e_1) + \cdots + \gamma_n g_n(e_n)
$$

(6)

In this equation, $\gamma_1, \cdots, \gamma_n$ are adjustable parameters, $g_i(e_i)$ can be of form in equation (5).

3.Main steam temperature control system for ultra supercritical unit based on ADRC

3.1. Specific solutions to main steam temperature control for ultra supercritical unit

Generally, to control the main steam temperature system for ultra supercritical unit, first the fuel water ratio is adjusted coarsely to improve steam temperature, then de-superheat by spraying as a fine adjustment, its fast dynamic response characteristic is helpful for fine adjustment on superheated steam temperature. Fuel water ratio adjustment requires maintaining a certain proportion of fuel and water, so that the intermediate point temperature can be controlled within a certain range, so as to ensure the hot spot temperature controllable [10]. In the adaptation to load changes, fuel and water must be kept in a correct relation and adjusted synchronously to maintain outlet temperature at the rated value steadily.

The difficulties to control ultra supercritical unit focus on fuel water ratio control, as the feedback signal of fuel water ratio cannot be both fast and accurate, which is a representative problem in the control system of ultra supercritical unit. As there's a great response delay of outlet steam temperature while the fuel water ratio changing, so it cannot use the outlet steam temperature to be the feedback signal of fuel water ratio. Now, in order to improve the speed and precision of fuel water ratio regulation, the intermediate point temperature is generally used as the correction signal of superheated steam temperature, because the changes of intermediate point temperature has much less delay than
superheated steam temperature does, and it is intuitive and conducive for the operator to control at the same time[11].

Therefore, the basic idea of main steam temperature control for ultra supercritical unit is as the following: focusing on the intermediate point temperature, coarse adjustment by fuel water ratio, fine adjustment by de-superheat water[12]. Although the precise fuel water ratio may ensure the main steam temperature can reach a certain steady value, in actual operation, there are still many factors influencing on main steam temperature, so a kind of controller with fast reaction speed, large regulation range, and strong anti-interference ability is needed to accurately adjust the fuel water ratio.

Generally, two stages of spray de-superheat water system is provided for ultra supercritical unit, the first stage is to be settled in front of platen superheater, the second stage is to be settled in front of finishing superheater. This design focused on the secondary stage superheater section. The following showed how ADRC was used in main steam temperature control system of supercritical boiler, ADRC used as the main regulator, PID as a vice regulator, the else sections remained invariant, ADRC of secondary stage spray de-superheating as shown in figure 2.

![Diagram showing the secondary stage de-superheat control system of superheated steam temperature](image)

**Figure 2.** Secondary stage de-superheat control system of superheated steam temperature
3.2. The operation process of ADRC control system

In Figure 2, the main regulator controlled the main steam outlet temperature of the boiler in the allowed range; the secondary regulator quickly eliminated all kinds of disturbances and controlled entrance temperature of high temperature superheater and outlet temperature of secondary spray de-superheaters. The main steam temperature, which was converted out by the function generator \( f_i(x) \), was set as the main regulator, ADRC’s superheated steam temperature value \( u(t) \). The secondary stage de-superheat control system of superheated steam temperature finely adjusted the outlet temperature of spray de-superheater, and controlled the superheated steam temperature in the allowable range. An add was used between the ADRC main regulator and PID secondary regulator, to receive the comprehensive feedforward disturbance signal \( w(t) \), which was formed by combined of signals from tilting angle of burner, the total air flow, the opening degree of auxiliary air baffle and the main steam pressure, etc. Boiler flue gas flow was introduced as a feedforward signal to remove the boiler load change's effects on superheated steam temperature, as the flue gas flow was a direct disturbance factor for superheated steam temperature. For convection superheater, the steam temperature increased while the boiler load or air flow increasing. The burner's angle was introduced as feedforward signal. \( w(t) \) could reduce the boiler load change's disturbance and pressure change's affect on superheated steam temperature. Usually, the relationship of changes between the feedforward signal and outlet temperature of spray desuperheater was typically nonlinear. Function generator \( f_2(x) \sim f_6(x) \) would convert each feedforward signal to a linear signal. The sum of \( w(t) \) and ADRC main regulator output signal \( u(t) \) was set as the value of the outlet temperature of secondary stage de-superheater. Since the instructions of air flow and tilting angle of burner, etc, was introduced as \( w(t) \), in the secondary stage de-superheat system, effectively reduced dynamic deviation of the final superheater outlet steam temperature, and improved the efficiency of whole superheated temperature control system.

In order to prevent leakage of de-superheater's secondary spray control valve, a spray break valve respectively was settled before and after the secondary spray regulating valve. During de-superheating spray, the spray break valve was full open or close. The PLW logic is as following: (1) when \( w(t) \), the main steam temperature, the temperature signal behind the secondary stage de-superheater, the secondary stage spray control valve, MFT or the load was lower than 20%, the secondary stage water spray control valve(M/A) was switched to M mode; (2) when the MFT action or load was lower than 20%, the secondary stage spray control valve was rapidly closed; (3) when the opening degree of secondary stage spray valve was greater than 5% and spray break valve closed, the opening degree of secondary stage spray valve was set at 1%; (4) when the opening degree of secondary stage spray valve was greater than 0%, the water spray stop valve was fully open.

3.3. Design of ADRC-PID controller

In the design of ADRC, the transition process was arranged reference to equation(2), if the parameters was selected as \( n = 3 \), \( \alpha = 10 \), \( \zeta = 0.92 \), \( \omega = 2 \), then the time domain expression of the transition process was as bellow:

\[
y^{(3)} + 82y^{(2)} + 75y^{(1)} + 23.4y = 81r
\]

(7)

The nonlinear functions of both ESO and NLC were equal to equation (5), when the settled signal \( r(t) \) made step change by 1mA, set ESO parameter as: \( \alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = 0.82 \);
\[ \delta = 0.015 \quad b_0 = 1.13 \quad \beta_1 = 21 \quad \beta_2 = 410 \quad \beta_3 = \beta_4 = 10000 \]
Set NLC parameter as:
\[ \alpha_1 = \alpha_2 = 0.95 \quad \alpha_3 = 0.96 \quad \delta = 0.01 \quad \gamma_1 = 0.02 \quad \gamma_2 = 0.8 \quad \gamma_3 = 1.2 \]

PID secondary regulator use PI regulation, here, \( K_p = 1.778 \quad T_i = 55.6S \).

4. Results of experiments

4.1. The constant disturbance experiment

Use the superheated steam temperature ADRC-PID control system into ultra supercritical 600MW unit to do a constant disturbance test on superheated steam temperature, set the disturbance quantity at 5 \(^\circ\)C; set the transition process of decay rate as \( \nu = 0.75 \sim 0.9 \), and stable period less than 15min; adjust process steady state deviation at 1 \(^\circ\)C, we can see that ADRC has a strong following performance. The curve of constant disturbance test is as shown in figure 3.

![Figure 3. Curve of superheated steam temperature constant disturbance test](image)

From the curve of operation in figure 3, we can see that object property changes has fewer affects on ADRC-PID, shows less steam temperature fluctuation during constant disturbance, and needs shorter time for system to restore stability. If slightly adjust the above parameters, the control quality will be further improved even.

4.2. Experiments on load variation

To do the load variation test within the variation rate of speed-up by 4%/min and speed-down by 2%/min, and to do the load adaptability test under the maximum variation rate of speed-up by 5%/min and speed-down by 3%/min, results of the above tests show that the unit run normally and have good adaptability under different operating conditions, and ADRC has strong robustness. See the test results as shown in table 1.
Table 1. Test results of unit's load variation

<table>
<thead>
<tr>
<th>project</th>
<th>high load areas</th>
<th>low load areas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Load increase</td>
<td>Load decrease</td>
</tr>
<tr>
<td></td>
<td>Load increase</td>
<td>Load decrease</td>
</tr>
<tr>
<td>load variation range/MW</td>
<td>350→700</td>
<td>700→350</td>
</tr>
<tr>
<td></td>
<td>700→700</td>
<td>700→350</td>
</tr>
<tr>
<td>Load variation rate /%·min</td>
<td>rate1</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>rate2</td>
<td>5</td>
</tr>
<tr>
<td>Pressure deviation of</td>
<td>Variable load</td>
<td>+0.35/-0.25</td>
</tr>
<tr>
<td>superheated steam /MPa</td>
<td>rate condition 1</td>
<td>+0.32/-0.27</td>
</tr>
<tr>
<td></td>
<td>Variable load</td>
<td>+0.40/-0.15</td>
</tr>
<tr>
<td></td>
<td>rate condition 2</td>
<td>+0.37/-0.37</td>
</tr>
<tr>
<td>Temperature deviation of</td>
<td>Variable load</td>
<td>+0.0/-2.5</td>
</tr>
<tr>
<td>superheated steam /℃</td>
<td>rate condition 1</td>
<td>+1.2/-1.3</td>
</tr>
<tr>
<td></td>
<td>Variable load</td>
<td>+0.2/-3.2</td>
</tr>
<tr>
<td></td>
<td>rate condition 2</td>
<td>+1.5/-1.3</td>
</tr>
</tbody>
</table>

5. Conclusions

The ultra supercritical unit has control characteristics of complex dynamics, operation mode of variable parameter and so on, so it's difficult to use the traditional design method to effectively control its superheated steam temperature. Against to thermal power plant's characteristics of great delay on superheated steam temperature control system, deficiency in performance under external disturbance and uncertainty of dynamic characteristics changing with conditions, this article proposed the ADRC design of superheated steam temperature. This design can achieve disturbance compensation without accurate model parameters.

By testing on the 600MW ultra supercritical unit, the superheated steam temperature fluctuated 1℃ during constant disturbance; in experiments on load variation, the unit run had good adaptability under different load operating conditions. the results show that, the control quality of ADRC technology, used to control superheated steam temperature of ultra supercritical unit, is superior to that of the traditional PID control, and proved that the ADRC control technology would have a good application prospect in control of superheated steam temperature for ultra supercritical unit.

6. Acknowledgements

Inner Mongolia University of Technology Fund (ZS201120)

7. References


