Intelligence-Based Hybrid Control for Power Plant Boiler

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Abstract—A hybrid classical/fuzzy control methodology is presented to integrate low-level machine control and high-level supervision for the steam temperature and water level processes of the power plant boiler. The coupling between two spraying systems can be reduced using hybrid coarse-fine intelligent control with qualitative decoupling strategy. A hierarchical fuzzy system is used for the water level control, instead of the human operator or the proportional integral derivative (PID) control. Industrial applications show the superiority of the proposed intelligent control over the traditional methods.

Index Terms—Feedforward control, hybrid control, intelligent control, multivariable control, proportional integral derivative (PID) control, steam water system, supervisory control, temperature control.

I. INTRODUCTION

THE BOILER system in a thermal power plant consists mainly of a steam-water system and combustion system, which produce a high-pressure superheated steam to drive a generator in order to produce power. The superheated steam temperature control and the separator water level control of a steam water system are very important to guarantee operation safety and to improve economic benefits of the power plant [1].

The superheated steam temperature process is regarded as a controllable process with multiple distributed parameters [2], large time-delay and unmeasurable disturbances. The water level of the steam separator (or the water level of drum) is important to economic operation of the boiler because it represents the balance between the superheated steam flow and the feedwater flow indirectly. There are uncertain disturbances and the effect of “false water level” for the water level process. The precise mathematical models of main steam temperature and water level of a separator can not be built easily. It is extremely difficult for conventional control theory to control such processes well.

Since the introduction of fuzzy set theory by Zadeh [3] and the first invention of a fuzzy controller by Mamadani [4], fuzzy control has gained a wide acceptance, due to the closeness of inference logic to human thinking, and has found applications in some power plants and power systems. It provides an effective means of converting the expert-type control knowledge into an automatic control strategy [5], [6]. Recently, Ling [7] proposes a model-based fuzzy gain scheduling technique and applies it to the real-time control of a laboratory-scale water–gas shift reactor. Mori and Kobayashi [8] propose an optimal fuzzy inference method for short-term load forecasting. Liu and Guan [9] apply a fuzzy set method to the optimal power flow problem. Su and Lin [10] propose a new approach using fuzzy set theory for voltage and reactive power control of power systems. As far as we know, there is no report of intelligent process control for the combined steam temperature and water level of the boiler in a large power plant.

The purpose of this paper is to introduce industrial applications of intelligent control of the steam temperature and water level of a steam boiler in a large-scale thermal power plant in China, using hybrid control methods. A better steam temperature performance is achieved using hybrid coarse-fine intelligent control. The serious coupling between sprayings can be successfully removed using a qualitative “decoupling strategy.” The fuzzy water-level control system simulates the experienced human operator for decision making and operating action. The industrial application results show that both steam temperature and water level can be maintained stable whenever disturbances are large or small, and a better control performance as compared to traditional methods is achieved.

II. THE MAIN STEAM TEMPERATURE AND SEPARATOR WATER LEVEL SYSTEM

A. Process Description

The investigated boiler of a 300-MW power unit is a compound circulatory tower boiler with low circulation ratio, which can produce 947 tons of steam per hour at a maximum continuous rating. The rated superheated steam pressure and temperature are 18.5 Mpa and 545 °C, respectively.

The boiler’s steam–water system is shown in Fig. 1. As the figure shows, the water is taken from the deaerator by using three motor-driven pumps. It goes through a high-pressure heater, feed-water valve SW or SWB, economizer, mixer, recycling pump, water wall, and arrives at the steam separator. The water in the separator circulates naturally through the water wall and mixer by recycling pumps, which absorbs radiating energy from the furnace continuously. The saturated steam produced through the above process flows out of the top of the separator, is reheated by the primary super heater, by the secondary super heater, and the third super heater in sequence. The product becomes high-pressure superheated steam (also called the main steam) in the end. The zero step spray desuperheaters (the zero step spraying) and the primary spray desuperheaters (the primary spraying) have two loops, respectively, while the secondary spray desuperheaters (the secondary spraying) has four loops. The primary spraying and the secondary spraying
are to maintain the exit steam temperature of the secondary super heater and the third super heater not higher than some maximum value, respectively.

1) Functional Analysis: The functional diagram of the steam water system can be described as shown in Fig. 2. The system can be classified into three subprocesses in terms of functions: process 0 to cover systems for separator water level, process 1 to cover systems dominated by the primary spraying control, and process 2 to cover systems dominated by the secondary spraying control. Two spraying systems are usually controlled via PID type controllers with human supervision in high-level for performance enhancement. The water level system is also controlled via a PID controller, however, the human operation is often required to replace the PID for a better performance.

The variables in Fig. 2 are explained as follows.

- \( W_F = \{t_F,F_F\} \): feed water temperature and flow;
- \( Q_i = \{t_i,F_i\} \) \((i=0,1,2,3)\): steam temperature and flow at different internal stages;
- \( Q_m = \{t_m,F_m\} \): main steam temperature and flow;
- \( W_P = \{t_p,F_p\} \): primary spraying water temperature and flow;
- \( W_S = \{t_S,F_S\} \): secondary spraying water temperature and flow;
- \( WL \): water level of the separator;
- \( V_P, V_S \): valve position of primary and secondary spraying;
- \( u \): control action to the feed water valve;
- process 2: generalized secondary spraying controlled process;
- process 1: generalized primary spraying controlled process;
- process 0: generalized separator water level controlled process;

2) Nonlinearity and Physical Limitation: There is strong nonlinearity in the system, which can be classified in detail as

a) Large time delay and uncertainties;
b) Unbalanced coupling between Primary and Secondary Spraying;
c) Primary Spraying delay time > Secondary Spraying delay time,
d) Primary Spraying valve capacity > Secondary Spraying valve capacity.
3) Technical Requirements: The control objective is to maintain a required steam temperature, which is classified as
1) The exit steam temperature of secondary super heater must be lower than 470 °C;
2) The main steam temperature must be lower than 560 °C.

B. Process Model and Dynamic Analysis

1) The Main Steam Temperature: The main steam temperature dynamics are too complex to model precisely. However, it can be described approximately using the following transfer function:

\[
 t_m(s) = \frac{T_{fm} s + K_{fm}}{T_1 s (T_2 s + 1)} \cdot F_m(s) + \frac{T_p s + K_p}{T_1 s (T_2 s + 1)} \cdot G(s) - \frac{T_p s + K_p}{T_1 s (T_2 s + 1)} \cdot (F_p(s) + F_s(s))
\]  

where

- \(T_{fm}\) expresses main steam flow item’s time constant;
- \(T_g\) expresses flue gas quantity of heat item’s time constant;
- \(T_p\) expresses time constant of the spraying item;
- \(T_1, T_2\) express main steam temperature time constant;
- \(K_{fm}, K_g, K_p\) express relative coefficients of each item, respectively;
- \(G(s)\) expresses “the flue gas quantity of heat.”

It can be seen that three factors can affect the main steam temperature variation. The first one is the main steam flow \(F_m\). The surge of the turbine load can cause the main steam flow to change, and then the heat transfer condition between the main steam and the flue gas will change along with it, which results in the main steam temperature variation. The second one is the quantity of heat from the flue gas side. The changes of fuel quantity, fuel type, feed draft fan gate, induced draft fan gate all will cause changes of flow speed and temperature of flue gas. Therefore it will change the heat transfer condition, and cause the main steam temperature variation. The third one is the spraying. The primary and secondary spraying \((F_p, F_s)\) are the control inputs to the main steam temperature. The super heater is a multivolume distributed parameter system. When the spraying changes, it will directly cause the variation of main steam temperature through multiple super heaters. The system has a large time delay property. Besides, traditional control methods used in Fig. 2 are not able to handle coupling between primary and secondary spraying systems, which results in further disturbance to the main steam temperature. In addition to the above factors, the separator water level, the main steam pressure, the water temperature, the water flow and the superheated steam blowing dusting, also have influence on the main steam temperature. Among them, the separator water level is most critical.

2) The Separator Water Level: Astrom and Ecklund [11] describe the dynamics of the water level of the steam separator approximatively using the following transfer function:

\[
 WL(s) = \frac{T_{ff} s + K_{ff}}{T_3 s (T_4 s + 1)} \cdot F_f(s) - \frac{T_{fm} s + K_{fm}}{T_3 s (T_4 s + 1)} \cdot F_m(s)
\]  

where

- \(T_{ff}\) expresses feed-water flow item’s time constant;
- \(T_{fm}\) expresses main steam flow item’s time constant;
- \(T_m\) expresses coal fuel quantity item’s time constant;
- \(T_3, T_4\) express water level time constant, respectively;
- \(K_{ff}, K_{fm}, K_M\) express relative coefficients of each item, respectively.
- \(M\) expresses coal fuel quantity.

From the equation (2), we can see that the three factors can affect the separator’s water level variation. The first one is the feed-water flow \(F_f\). The surge of the feed-water pump’s exit pressure can cause the feed-water flow to change. Therefore the change of the feed-water valve position can also cause a surge of the water level. The second one is the main steam flow \(F_m\). The pressure in the separator will change along with the saturated steam flow. The water level can be affected not only by the unbalance of the input and output actuating medium, but also by the change of the air bubble’s volume in water caused by pressure (called “false water level”). The third one is the coal fuel quantity \(M\), which changes steam flow and eventually influences the water level.

C. Traditional Control Methods

1) The Main Steam Temperature: Since the primary spraying system has larger capacity than the secondary spraying system, the primary-secondary spraying system is an unbalanced multivariable process. The primary system provides the nominal performance and the secondary system does a fine-tuning to the main steam temperature.

The traditional control method for the primary spraying system is a PI-like “temperature difference” control as shown in Fig. 3. The fixed load-temperature \(t(F)\) provides a setpoint to the primary spraying system according to the steam flow output \(F_m\). The traditional control method for the secondary spraying system is a cascade PID control with the auxiliary load feedback action as shown in Fig. 4. The auxiliary loop feedbacks steam.
temperature $t_{3}$ (after secondary spraying) to suppress inner disturbance and maintain quick response using a simple proportional control $K$.

Though “temperature difference” control for the primary system has considered the effects from the secondary system, in general, there is a lack of good coordination between the two spraying systems. Besides, the fixed gain control systems on both sides have a poor adaptation to large uncertainty and varying dynamics even if the PID controller is well tuned using the Ziegler–Nichols method. To satisfy the technical requirement, a human operation is required from time to time to adjust the control system.

2) The Separator Water Level: Since the water level of the steam separator also affects the final steam temperature, proper water control is very necessary in the separator. The water level process is usually controlled via a cascade PID as shown in Fig. 5. The feedforward signal can avoid the false action of valve position when the “false water level” happens. The gain or coefficients $K$, $K_m$, and $K_F$ are fixed parameters.

Since the water level process is very complex, the performance of the PID may not be very satisfactory. However, the experienced operator can often achieve a better performance on site. If the high performance is required, the manual control has to be used. The human control includes the following three main parts as shown in Fig. 6.

3) Perception: Through the on-site observation and theoretical analysis, the information required for manual control includes the following.

- The actual water level $WL_0$ of the separator and its set point value $WL_0$ of the water level;
- The main steam flow $F_m$, the feed-water flow $F_f$, the primary spraying $F_p$, and secondary spraying $F_s$;
- The coal feeder’s total revolution $M$ (coal fuel quantity) and the actual power $AP$.

4) Decision Making: The human operator decides proper control action according to the changing conditions of water level difference.

5) Operating Action: Normally, the operator gives actual adjustment quantity according to the water level difference $e_3$, the balance relationship $e_2$ between input water flow (feed-water flow and spraying) and the main steam flow, and the difference $e_3$ between the actual coal fuel quantity and the actual power.

**Summary:** Due to the complexity and coupling of the process, the traditional control methods do not demonstrate satisfactory performance. In industry, however, the experienced operator can gain better performance as long as he can continuously monitor the process and always make the right decision, though inconsistency could be introduced due to variation on human experience and conditions. To further improve the performance and reduce reliance of a human being, various intelligent systems should be developed to replace the human operator on working with classical controllers and integration of both machine-level control and high-level supervision.

### III. INTELLIGENT CONTROL METHODOLOGY

#### A. Hybrid Intelligent Control of Steam Temperature

A better coordination between two spraying systems is essential for a better performance. On machine-level, a coarse-fine control strategy is operated according to the capacity of two spraying systems. The adaptation algorithm is added to achieve robustness to dynamic variation. Furthermore, the new control system is developed from the traditional one to have the minimum implementation work and reconstruction. On the high-level supervision, fuzzy expert systems, developed from human experience, are used to improve the decoupling effect and increase the intelligence of the control system as well.

1) Intelligent Coarse Control for Primary Spraying Process: The human operator can decide the valve position of the primary spraying according to the valve position of the secondary spraying. These experiences for “valve position” control can be summarized as

- If the valve position of the secondary spraying $V_s$ changes within 30%~70%, the valve position of primary spraying $V_p$ should not be changed. The normal set-point value of primary spraying valve position is 30%.
- On the other hand, if the $V_s$ is lower than 30% or higher than 70%, the operator considers that the valve position of primary spraying $V_p$ should be closed or opened wider.

2) Qualitative Decoupling Strategy: Based on the above human experience, decoupling rules could be developed for high-level supervision, by placement of the human operator.
Fig. 7. “Override” control for primary spraying process.

Rule 1 — When \( V_s \) changes within 30%~70%, then \( V_p \) keeps at original valve position.

Rule 2 — When \( V_s \) is lower than 30% or higher than 70%, then \( V_p \) is set to be zero or a larger value using the following two sub-rules.

Rule 2a — When \( T_2 \geq 470 \, ^\circ C \), it still takes the “temperature difference” between the front and back of the secondary spraying as a controlled variable to guarantee super heater operating safety.

Rule 2b — When \( T_2 < 470 \, ^\circ C \), it takes the “valve position” as the controlled variable to initiate decoupling the interaction between Primary and Secondary Spraying.

The so-called “override” control is suggested in Fig. 7 to handle the physical limitation 2) and 4), and achieve the technical requirement 1) for “coarse control” of \( t_m \). This intelligent control switches between the traditional PI-type “temperature difference” control and the newly added “valve position” control under qualitative decoupling strategy. The new system is easy to implement without large reconstruction to the original system.

Fig. 8. Hybrid classical/fuzzy control method for secondary spraying process.

4) Fuzzy PI With Gain Scheduling: The standard fuzzy-PI controller is used as shown in Fig. 8, together with the standard triangular membership functions and linear rule base [6], [12], which has been popularly used in many fuzzy control research and applications. Each input variable takes seven membership functions. Two inputs to the fuzzy system are the difference of main steam temperature \( \Delta e \) and its changing rate \( \Delta e \). The fuzzy output \( u_P \) is added to output of the cascade PID control system. The output gain \( K_f \) is scheduled using the following strategy.

- When the main steam temperature difference is large, a large output gain is used for fuzzy control to have a larger effect on the main steam temperature, which can suppress disturbances and have a quick system response. The traditional PID system plays as an auxiliary role under this circumstance.
- When the main steam temperature difference is small, a small output gain is used to have a smaller fuzzy effect on the main steam temperature. In this situation, the traditional PID system provides primary control action to the main steam temperature, and the fuzzy system only plays as a fine-tuning.

B. Intelligent Water Level Control

In industry, the experienced operator could gain a better performance than the traditional PID control as long as he can monitor the process continuously without making error. To provide better and reliable performance, an intelligent control system should be developed to replace the manual control.

In order to simulate functions of information processing, decision making and operating action of the experienced human operator, an intelligent control framework is proposed in Fig. 9 for the separator water level control, with two main parts.

- A multivariable fuzzy controller for the human operating action.
- An intelligent coordinator for the human decision making process.

1) Multivariable Fuzzy Controller: The boiler’s water level is a typical multivariable control system. The rules’ number of the traditional multivariable fuzzy control will exponentially increase along with the increment of the variable’s number [13], [14], which makes control difficult. Here three independent low-dimensional fuzzy systems are used in an innovative way in Fig. 10, to construct a distributed type multivariable fuzzy system [15], [16], for controlling the feed-water valve.
The first fuzzy system determines proper valve position of the feed-water based on the water level difference $e_1$ and its changing rate $\Delta e_1$. The inference rule base is made up of a set of linear rules [6]. In order to improve the adaptive capability of the fuzzy controller, a gain-scheduling mechanism is developed for the two input gains $K_{e1}$ and $K_{d1}$, which are changed according to different stages of the dynamic process. The adaptation rules for $K_{e1}$ are shown in Table I, and rules for $K_{d1}$ are happened to be opposite to that of $K_{e1}$, where, N, P, B, M, S, and Z mean Negative, Positive, Big, Middle, Small, and Zero, respectively.

The secondary fuzzy system provides a control signal based on the flow balance $\Delta y$ with rules shown in Table II. The third fuzzy system provides a control signal based on the difference between the actual coal feeder’s total revolution $\Delta M$ and the actual power $\Delta P$, with inference rules coinciding with that in Table II.

The multivariable fuzzy controller of separator water level is made up of the above three subordinate fuzzy controllers. The subordinate fuzzy controller I plays a dominant role in control, and others act as auxiliary functions to overcome the “false water level.”

2) The Intelligent Coordinator: The experienced human operator can maintain desired performance over a wide range of operating conditions. This decision-making process can be replaced by an intelligent coordinator to cooperate with the multivariable fuzzy controller at the machine-level. Through problem analysis and experience extraction, linguistic rules of the intelligent coordinator could be summarized as below.

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IV. INDUSTRIAL APPLICATION

The proposed hybrid intelligence-based control methodology has been used in the main steam temperature control system and the steam separator’s water level control system of the 300 MW power unit of Yuan Bao Shan Power Plant in China for more than three years. PID controllers used on site are...
well tuned using Ziegler–Nichols methods. Under the same operating conditions and variations of load, both traditional PID controls and the proposed intelligent approaches are compared as in Figs. 11–14.

There are two large load surges in the operation, one rises from 185 MW to 300 MW in a period of 0→14 min, and the other drops from 300 MW to 200 MW in a period of 60→70 min. The main steam temperature surges ±12 °C for the traditional PID control in Fig. 11, but ±4 °C for the hybrid intelligent control in Fig. 12. The added intelligence has successfully simulated a human operator to improve the adaptation capability of the traditional PID system. For the same load surge, the separator water level surges ±5 m for the traditional cascade PID control in Fig. 13, but ±2 m for the intelligent control in Fig. 14. The proposed intelligent system has successfully replaced the human operator and shown better performance than PID control. In general, the proposed intelligence-based hybrid control systems meets technical requirement and produces a good economic benefit.

V. CONCLUSION

Intelligence-based hybrid control methodology is proposed in this paper to integrate machine-level control and high-level supervision properly for performance improvement of steam temperature and water level processes. The methods have been implemented for a power plant in China with the following key features.

- The steam temperature control is greatly improved by hybrid coarse-fine intelligent control for primary-secondary spraying processes, with significantly reduced primary-secondary coupling.
- The above hybrid intelligent control system is easy to implement without large modification to the original system.
- The intelligent control system for the water level control has successfully replaced the human operator to gain robust performance.

The real industrial operation demonstrates that a better performance than traditional methods is achieved for both steam temperature and water level processes.

REFERENCES


