Research and Design on the Coordinate Control System of Once-through Boiler Power Unit

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Abstract. Taking the 1000 MW ultra supercritical unit as an object of study, the nonlinear model is built through mechanism analysis, which is linearized based on small error, the multi-variable decoupling controller is designed to achieve full decoupling of the input and output variables, and finally the three-input-three-output coordinated control system (CCS) is established. The control system is verified by coal quality and the specific enthalpy of feed water disturbance when load changing, the simulation result shows that the improved CCS has good control performance.

1. Introduction

In order to save energy and reduce environmental pollution, the coal power technology must be optimized and developed. Therefore, the supercritical once-through boiler unit with large capacity, high power generation efficiency and strong load adaptability has become the main thermal power unit in China\cite{1}. With the implementation of the sustainable development strategy of power industry, the integrated automation of power network puts forward higher requirements for the performance of CCS.

Once-through boiler unit CCS of the object structure model is usually simplified as three-input-three-output system\cite{2}. The inputs of the system are the water mass flow rate, fuel quantity and the opening of the steam turbine valve. The outputs are the intermediate point temperature and main steam pressure and steam turbine power, cross correlation and strong coupling phenomenon exists between the input and output variables.

In the CCS of the once-through boiler unit, the most important is the feed water flow regulation and fuel quantity regulation\cite{3}. Through the correct coordinated action and coordination of the regulation system, the boiler load can meet the requirements and the main steam temperature can be kept stable. Because the change of fuel quantity and feed water flow have obvious influence on
the output power, the intermediate temperature is generally controlled by adjusting the coefficient of fuel-water ratio, and the three-input-three-output boiler unit model is simplified to the double-input-double-output model, so there are two different schemes in practical engineering application[4]. Scheme 1: The feed water flow changes with the fuel quantity, changing the fuel quantity to adjust the load or main steam pressure, changing the feed water to adjust the intermediate point temperature. Scheme 2: The fuel quantity changes with the feed water flow, change the feed water flow regulating load or main steam pressure, change the fuel quantity to adjust the temperature difference before and after the spray desuperheater in the micro-overheated section, ensure the fuel-water-ratio, and realize the coarse adjustment of the overheated steam temperature. However, these two schemes have their own advantages and disadvantages. Since the feed water flow is regulated much faster than the fuel, Scheme 1 is conducive to the control of the main steam temperature, but the main steam pressure will fluctuate greatly, while Scheme 2 is conducive to the control of the main steam pressure, but not conducive to the maintenance of the main steam temperature. In addition, due to frequent changes in coal quality, it is difficult to ensure the coefficient of coal-water-ratio, which often causes problems such as large parameter fluctuation range and poor load adaptability of the unit during operation.

Based on the above situation, the author established the nonlinear mechanism model of the once-through boiler unit by reasonable simplification, linearized the model by using the small deviation method, designed the corresponding multi-variable decoupling compensator, and realized the complete decoupling of the steam turbine and the boiler, the feed water and the fuel. The control scheme of the once-through boiler unit CCS based on dynamic decoupling is proposed in the paper.

2. Simplified model of once-through boiler unit

The steam water separator is the dividing point between the evaporation and overheating of the working medium of the once-through boiler. The temperature (specific enthalpy) of the outlet (intermediate point) working medium reflects the rationality of the match between fuel and feed water. It is one of the important state parameters to characterize the operation of the through-through boiler. As a feedback signal of water-burning ratio, the specific enthalpy of the intermediate point has obvious advantages in sensitivity and linearity when the load changes [5]. In addition, since the physical concept of enthalpy value is clear, it is more scientific to analyze the heat absorption distribution of each heating surface by using enthalpy increment.

Taking the outlet of the steam water separator as the boundary, the once-through boiler is divided into high specific heat capacity heating section and overheating section respectively. The whole once-through boiler unit is divided into four parts: pulverizing system, boiler heating system, boiler overheating system and steam turbine. The energy conversion and heat transfer process of the whole unit is divided into three stages: combustion and heat transfer in furnace, pipeline transfer and steam turbine work.

2.1. Pulverizing system

The dynamic characteristics of the pulverizing system can be described as

\[ k_I \frac{dR_I}{dt} = u_b e^{-\tau} - r_b \]  

(1)

where \( u_b \) is fuel command, kg/s. \( \tau \) is the delay time, secon-
ds. $k_i$ is the inertial time in seconds. $r_f$ is the output of mill, kg/s. Due to the dynamic time of combustion process and water wall heat transfer in furnace is much smaller than the dynamic time of pulverizing. There is a definite proportional relationship between the amount of fuel entering the boiler $r_f$ and the effective heat absorption of the boiler[6]

$$Q = k_i r_f$$

where $k_i$ is the combustion gain.

A. Once-through Boiler Unit

The dynamic characteristics of the evaporate heating surface of a once-through boiler[7] can be describes as

$$C_1 \frac{dh_m}{dt} = q_{m,ec} (h_{ec} - h_m) + Q_t$$

The over-heater dynamic characteristics are as follows

$$C_2 \frac{dp_t}{dt} = q_{m,att} h_{ec} + q_{m,ec} h_m - q_{m,t} h_t + Q_{st}$$

The flow of steam into the turbine is related to the main steam pressure and the valve opening of the turbine [8].

$$q_{m,t} = k_3 \mu_t p_t$$

Without considering the reheater, the relationship between the steam input and output power of the turbine $N_t$ can be expressed as follow

$$N_t = k_5 q_{m,t} (h_t - h_{ec})$$

where $k_3$ and $k_5$ are gain coefficient. $q_{m,ec}$, $q_{m,att}$ and $q_{m,t}$ are mass flow of economizer inlet, separator outlet and main steam respectively, kg/s. $h_{ec}$, $h_{se}$ and $h_t$ are the specific enthalpy of economizer inlet and separator outlet respectively, kJ/kg. $M$ is the density of the working fluid at separator outlet, kg/m. $Q$ and $Q_{st}$ are the effective absorption of the water wall and overheated system, kJ/s. $C_1$ and $C_2$ are the heat storage coefficient of evaporator sections and overheated sections respectively.

2.2. Simplified model of once-through boiler unit

The heat storage coefficient of the once-through boiler decreases with the increase of pressure. the heat storage of metal is much larger than that of working medium, and the changing trend of the heat storage of boiler is consistent with that of metal [9]. In order to facilitate the analysis of the dynamic characteristics of the boiler system in a certain range, it can be considered that the heat storage coefficient of the evaporation heating surface is a function of the specific enthalpy of the intermediate point, and the heat storage coefficient of the superheater is a function of the main steam pressure.

The dynamic characteristics of once-through boiler is made up of evaporate surface and superheater, under stable conditions the steam flow of superheater outlet is equal to the sum of feed water and sprayer.

$$q_{m,ec} + q_{m,att} = q_{m,st}$$

Make $n = (h_{st} - h_{m})/(h_{se} - h_{m})$, that is the ratio of specific enthalpy incremental of superheater with evaporator, it also shows the thermal energy distribution ratio in the process of boiler heating. The thermal energy absorbed by evaporator can be written as
\[ Q_i = \frac{q_{m,ec}}{(n+1)q_{m,t}} Q \approx \frac{Q}{n+1} \]  

above all, the three-input-three-output dynamic model can be deduced as

\[ \dot{Q} = k_i r_i e^{-\sigma} / (k_i s + 1) \]  

\[ C_1 \frac{dh_m}{dt} = q_{m,ec} (h_{ec} - h_m) + Q / (n+1) \]  

\[ C_2 \frac{dp_t}{dt} = [q_{m,ec} - (n+1)q_{m,f}] (h_m - h_{ec}) + nQ / (n+1) \]  

\[ D_t = k_2 p_t \mu_t \]  

\[ N_E = (n+1)k_3 q_{m,1} (h_m - h_{ec}) \]  

3. Once-through boiler unit CCS design

The control objects of the furnace show strong nonlinear characteristics and the control loops of the furnace are coupled with each other when the load changes in a large range of thermal power units. At present, the basic design ideas of unit coordinated control are based on the unidirectional or bidirectional compensation decoupling control based on the control of machine and furnace or furnace and machine. Decoupling design in engineering is mostly obtained from experience, but there are also rules to follow in theoretical analysis.

According to the decoupling compensator, the unit coordinated control structure can be obtained, as shown in Figure 1. Complete decoupling between the turbine side and the boiler side, and between the feed water side and the fuel side in the boiler can be realized.

The influence of turbine side disturbance on the enthalpy of intermediate point is negligible. To the introduction of the main steam pressure deviation signal to the turbine side, which can be used to compensate water side and fuel side may cause disturbance of the steam turbine regulator action, because the main steam pressure and power to fuel and feed water disturbance response curve shape similar, with the change of turbine power deviation signal changes offset each other, guarantee of the opening of the steam turbine tone remain the same when boiler lateral disturbance. As a compensation signal for turbine side disturbance, it is introduced into the feed
water side and the fuel side. When turbine side disturbance occurs, since the power and the specific enthalpy of the intermediate point change in the opposite direction, the feed water side action is accelerated to ensure the stability of main steam pressure and improve the response capacity of the system while the fuel side instruction remains unchanged. In addition, when change the power setting value, the change of the steam turbine governor quickly, makes the steam turbine regulating valve (like the steam turbine is tone? Full please change all unified] action to keep up with the load instruction needs, but due to the inertia of boiler is very big, difficult to replenish energy, will cause the main steam pressure fluctuations, even exceed the permitted scope of deviation, The turbine regulator will be introduced to stabilize the main steam pressure.

When the fuel side is disturbed, the specific enthalpy of the intermediate point changes in the same direction as the main steam pressure, while when the feed water side is disturbed, the specific enthalpy of the intermediate point changes in the opposite direction as the main steam pressure. And differential signal at the same time introducing the feed water side and fuel side, can reduce or eliminate the coupling between water side and fuel side, makes it easy to system setting, at the same time, it is equivalent to the boiler side adds a rapid feedback loop that can compensate the disturbance of steam turbine side, improve the response speed of the unit load, enhances the ability of system to overcome the disturbance.

4. Simulation

A 1000 MW once-through boiler unit is taken as the control object. The inputs are feed water flow, fuel quantity and steam turbine valve opening, and the outputs are specific enthalpy of intermediate point, main steam pressure and steam turbine power.

In order to verify the control performance of the coordinated control system, load lifting experiments were carried out on the system. Condition 1: the unit load was increased from 677 MW to 802 MW; Condition 2: The load of the unit was reduced from 934 MW to 802 MW. Figure 2 and Figure 3 show the set values and response curves of turbine power, intermediate point specific enthalpy and main steam pressure output under two working conditions. Due to the fast response speed, feed water quality traffic based on the water of coal and water control, on the main steam pressure and steam turbine power adjustment, overshoot and regulating time are better than the control of water with coal, but the water supply to the middle point is greater than the influence of the enthalpy, making the point than the enthalpy of large range, adjust time, is not conducive to keep the main steam temperature. Using three input three output decoupling compensator of coordinated control mode, three output overshoot and adjustment time is better than that of traditional coal with two methods for regulating water and water with coal, the main steam pressure and steam turbine power has good dynamic performance, the intermediate point enthalpy has certain dynamic deviation, in the process of adjusting its range and adjust time significantly reduced, The control of the whole CCS has good performance.
Fig. 2 The CCS response curves of up loads

(a) Steam turbine power response curve

(b) Main steam pressure response curve

(c) Specific enthalpy response curve
The CCS response curves of down loads

(a) Steam turbine power response curve

(b) Main steam pressure response curve

(c) Specific enthalpy response curve

Fig. 3 The CCS response curves of down loads
5. Conclusion
A new three-input-three-output control strategy is proposed for the coordinated control system of the once-through boiler unit by introducing dynamic decoupling structure. The dynamic compensation decoupling between the steam turbine and the boiler, the feed water and the fuel is realized, which effectively solves the problems such as difficult to ensure the coefficient of coal-water-ratio, large fluctuation range of unit operating parameters and poor adaptability of unit load. The simulation results show that the proposed method has good dynamic decoupling performance and load adaptability, and has good practical application value.

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