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## Optimal Control System Based on Advanced Control Technology in Ultra Supercritical Power Units

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**Abstract:** Aiming at problems existed in 700 MW ultra supercritical power units in a power plant, such as low load changing rate, low load regulation accuracy and instability of the control system caused by coal type changing, the coordinated control system and advanced optimal steam temperature control system are proposed through adopting the advanced control methods in the modern control theory. The practical application showed that the advanced optimal control systems have successfully improved the performance of load regulation and reduced the fluctuation of key parameters and greatly enhanced the operation stability and self-adaptability to coal variation of the units.

**Key words:** Ultra supercritical power unit, coordinated control system, steam temperature control system, predictive control, neural network, self-adaption

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### INTRODUCTION

Two 700MW ultra supercritical power units in a power plant were brought into production in December, 2009 and February, 2010. The type II once-through boiler is ultra supercritical of variable pressure spiral pipes with single furnace, An intermediate reheat, balanced draft, dry slagging, all-steel structure and full suspension structure. Its DCS is OVATION. Before the optimal control systems are directed, traditional regulation scheme, combined of load instruction feed-forward and feedback of PID, are used as CCS (coordinated control system) and conventional cascade control system is used as superheated steam temperature control system. Although reheated steam control system is supposed to be adjusted by spray desuperheating and dampers, primary cascade control scheme can hardly be controlled automatically by dampers because of a large lag of dampers regulation. So, spray desuperheating is used as reheated steam temperature control method which decreases the economics of the units. The problems of the control system are analyzed in this study and optimal unit control system improvement design, based on advanced control technology, is proposed as well.

### PROBLEMS OF PRIMARY CONTROL SYSTEM

The dynamic characteristics of unit controlled objects are bad because the coal combustion changes frequently.

Normal PID control systems are hard to control objects of large time delay, great inertia and time-varying system efficiently (Zhang *et al.*, 2011). The situation always makes regulation characteristics not fitted with the thermal process requirements of stability and optimal performances and are shown in details below.

**Undesirable load regulation performance:** Load changing rate is slow and setting from 3MW per minute to 5 MW per minute, as well as overregulation of power unit load and undesirable regulation precision (Lu, 1990).

**Large fluctuation of key parameters:** Main steam pressure, steam separator temperature, main steam temperature and reheating steam temperature fluctuate in the process. In process of increasing and decreasing load, dynamic quality indicators of main steam pressure are beyond 1.0 MPa. And temperature of steam separator, main steam and reheated steam are between 15 and 20°C. Big fluctuation of key parameters leads to fluctuation of inlet coal mass and feed-water flow. Primary CCS load changing curve is shown in Fig. 1.

**Bad adaptability for coal type:** When coal type changing, CCS and steam temperature control system qualities are slow and it just can be operated manually for maintaining stability (Li *et al.*, 2011; Chang and Tsai, 2011).

According to practical problems above, coordinated and advanced optimal steam temperature control system



Fig. 1: The load response curve of original CCS

are based on advanced control technology through predictive control (Camacho and Bordons, 2004; Orłowski, 2011), neural network and so on (Wu *et al.*, 2009). Practical application shows that advanced optimal control system enhances regulation quality of unit load, decreases fluctuation of key variable quality and increases operating stability and adaptation of coal type.

#### COORDINATED CONTROL SCHEME BASED ON ADVANCED CONTROL TECHNOLOGY

Based on existed problems, this study mentions control technologies, like predictive control, neural network and intelligent feed-forward (Hua *et al.*, 2005) and proposes scheme of coordinated control system which is shown in Fig. 2.

On control structure, new coordinated scheme maintains feed-forward and backward control scheme of regular boiler control plan and gets improvement in three aspects.

**Adopting predictive controller as backward regulator:** In backward loop, regular PID controllers are replaced with

advanced GPC controllers. PID regulators calculate control actions with present and previous controlled deviation. But GPC makes control calculation with predictive value of regulated variables. Obviously, GPC can control and regulate in advance which is fitted for large delay process. In the implement of predictive control algorithm, closed loop structure of predictive control is mentioned in reference (Du and Ling, 2010; Hua *et al.*, 2005) which is shown in Fig. 3.

In Fig. 3,  $sp$ ,  $u$ ,  $y$  are setting value, control function and controlled variable respectively.  $Ru(q^{-1})$ ,  $Ry(q^{-1})$  and  $r$  are parameter polynomial of predictive controller. We can get the Auto-Regressive-Moving-Average (ARMA) model of controlled process in Eq. 1:

$$A(q^{-1})y(k) = B(q^{-1})u(k-1) + \frac{w(k)}{\Delta} \quad (1)$$

$y(k)$  and  $u(k-1)$  are controlled variable and controlled function of every sample time.  $w(k)$  is unrelated random disturbance sequence.  $\Delta = 1 - q^{-1}$  represents the difference operator and  $q^{-1}$  is backward shift operator.  $A(q^{-1})$ ,  $B(q^{-1})$  are polynomial of  $q^{-1}$ :

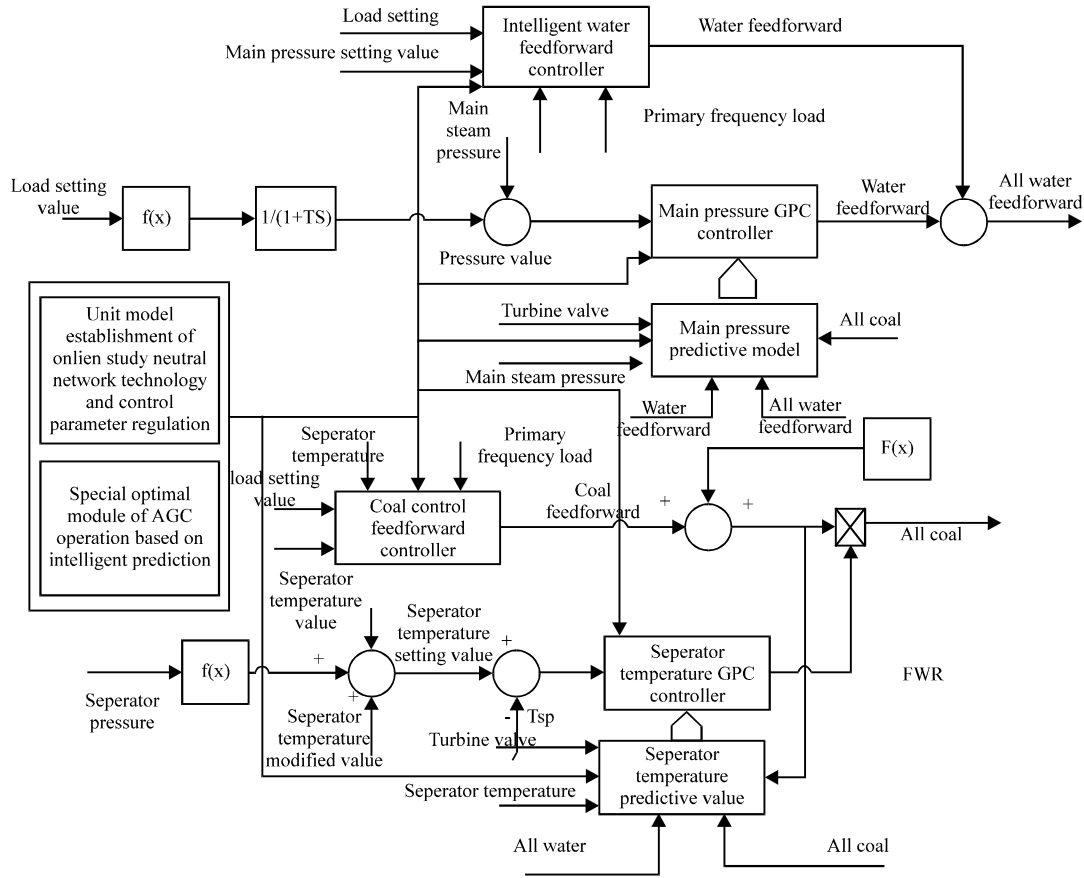


Fig. 2: New coordinated strategy based on advanced control technology

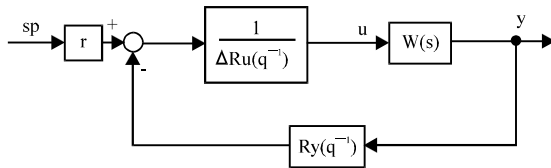


Fig. 3: The closed-loop structure of predictive control system

$$\begin{aligned} A(q^{-1}) &= 1 + a_1 q^{-1} + \dots + a_{na} q^{-na} \\ B(q^{-1}) &= b_0 + b_1 q^{-1} + \dots + b_{nb} q^{-nb} \end{aligned} \quad (2)$$

In the optimal control project described in this article, transfer function model of burning capacity and main-steam obtained in field are below:

$$W(s) = \frac{MSP(s)}{FU(s)} = \frac{0.0581}{(1+160s)(1+600s)} \text{ MPa/t/h} \quad (3)$$

MPS is main-steam pressure (MPa). FU is fuel (t/h). Sample time is 10s. Bilinear transformation of transfer function model of Eq. 3 is ARMA model.

$$\begin{aligned} (1 - 1.918955q^{-1} + 0.9200213q^{-2})MSP(k) = \\ (1.54892 \times 10^{-5} + 3.097841 \times 10^{-5} q^{-1} + \\ 1.54892 \times 10^{-5} q^{-2})FU(k-1) + \frac{1}{\Delta} w(k) \end{aligned} \quad (4)$$

After calculating, polynomials of all predictive controllers are below:

$$\begin{aligned} Ru(q^{-1}) &= 1 + 2.75793 \times 10^{-2} q^{-1} + 9.214459 \times 10^{-3} q^{-2} \\ Ry(q^{-1}) &= 5.989805 \times 10^2 - 1.145384 \times 10^3 q^{-1} + 5.473166 \times 10^2 q^{-2} \\ r &= 0.9131 \end{aligned} \quad (5)$$

In practical optimal control, we can get mathematical model of controlled process on many load points and parameter polynomials of various predictive control systems. And we also switch parameter polynomials of predictive control.

**Control system regulation online of fitted unit operation and coal type changing by neural network technology:** As for regulation control scheme, based on PID of DCS

implement, control system parameters are hard to regulate when unit operation and coal type changes which leads to bad self-adaption. New coordinated control system uses RBF neural network technology to build reaction unit operation and nonlinear network model of changing coal type. It can also adjust advanced control algorithm parameters automatically online and make sure the whole control system has good control performance when unit operation and coal type changing.

**Replacing intelligent feed-forward of traditional proportional differential feed-forward:** Traditional boiler load feed-forward instruction is just PID load feed-forward instruction. In the process of increasing and decreasing load, no matter what kind of operating condition is, its feed-forward is stable instantly. Intelligent feed-forward is a kind of feed-forward, intimating human operation. The added feed-forward and practical operating condition is related closely. If main-steam pressure is higher than setting value and is able to rise at the starting moment of reducing load, we decrease feed-forward of boiler load instruction. In practical calculating, we make main-steam pressure deviation and fuzzy changing rate and they are divided into 7 fuzzy grades and then we calculate feed-forward of boiler load instruction which is related with practical operating condition.

## NEW REHEATING STEAM TEMPERATURE CONTROL SYSTEM

New damper control system, as main control loop of reheating steam temperature regulation, is based on fuzzy intelligent feed-forward and predictive control technology (Zhang *et al.*, 2012). New control system is shown in Fig. 4. The unit load in the figure is dynamic model of Table 1.

Feedback control loop combines many long delay control technologies organically, like generalized predictive control technique, self-adaption Smith feature compensation technique, phase compensation technique, to speed up damper regulation rates and inhibit reheating stem temperature with respect of ensuring stability.

Table 1: The dynamic mathematical model of gas damper for reheat steam temperature adjustment

Load	Model
580 MW	$\frac{0.8367}{(1+45s)^2(1+112s)^2}e^{-137s}$
470 MW	$\frac{0.699}{(1+93s)^2(1+157s)^2}e^{-165s}$
340 MW	$\frac{0.3821}{(1+94s)^2(1+221s)^2}e^{-196s}$

Ps: s is Laplace operator

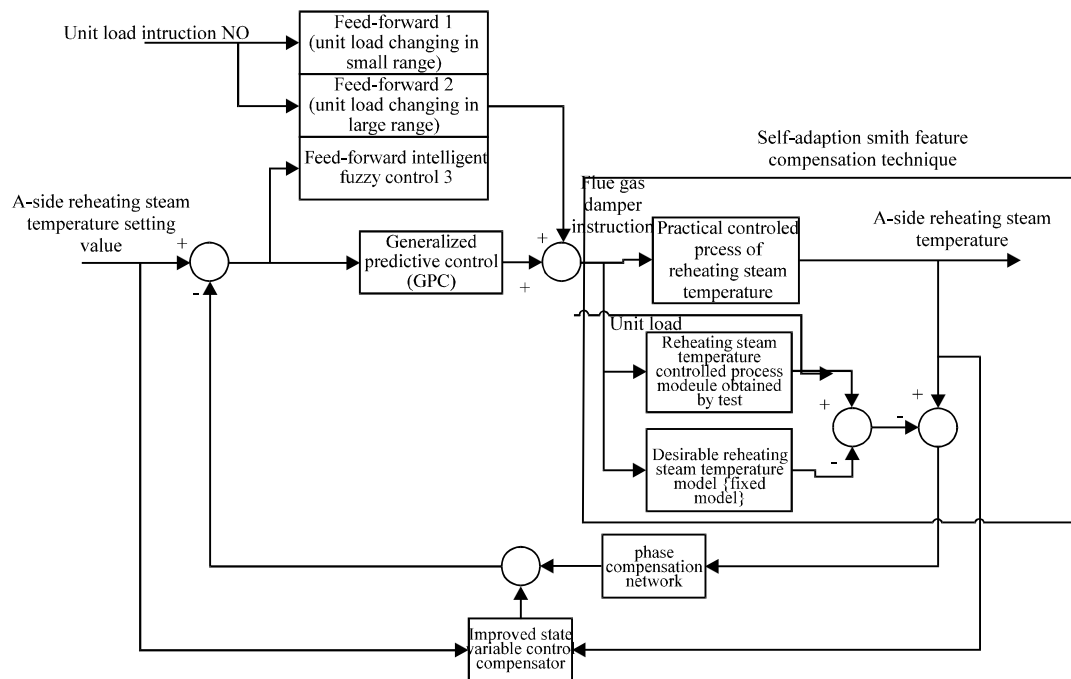


Fig. 4: The structure of new reheating steam temperature control system

**Self-adaption Smith feature compensation technique:**

Shown in Fig. 4, main purpose of self-adaption Smith feature compensation technique is compensating time delay of controlled object (Chang *et al.*, 2010; Sun *et al.*, 2010). And there are advantages of two respects.

After compensating characteristics, the equivalent controlled objects of reheating steam temperature are the selected mathematical models. They make dynamic characteristics and unit load unrelated which are beneficial for generalized predictive control and other advanced controller design and setting.

Because equivalent object of reheating steam temperature is selected by man, its inertia time is small, compared with the practical which is good for increasing its stability. As for self-adaption Smith feature compensation technique, model precision requirements of controlled process are strict which require owning precise dynamic model on many load points. On 3 load points, the precise reheating steam temperature control process model is obtained, shown in Table 1. We get better control effect with adoption of model design in Table 1.

**Phrase compensation technique:** Phrase compensation technique is mainly inserting 2 lead/slag links and uses lead characteristics of lead/slag links to balance out inertia time. Thus, it makes the inertia time of the compensated generalized steam temperature quite small which is beneficial for improving the rapidity and stability of the whole system.

**State variable controller:** Using state variable controller can estimate online temperature of reheater process. Drawing the temperature estimated values into reheating steam control system improves action time efficiently and speeds up regulation rates of reheating gas dampers, suppresses the influence of variable disturbances. As for the mathematical model in Table 1, related reheating steam temperature state variable controller is constructed conveniently with references (Chang *et al.*, 2010; Hua *et al.*, 2005).

**Generalized predictive controller:** With mathematical model of reheating steam temperature, generalized predictive control can predict future changing trend of reheating steam temperature. We can regulate dampers to compensate influence of object long delay efficiently (Niu *et al.*, 2011), according to future tendency. In practical application, we also adopt predictive control loop backward structure in Fig. 3. Calculating parameters polynomial method of reheating temperature predictive controller (Huang *et al.*, 2008) is as same as the introduced above.

**IMPLEMENTATION OF OPTIMAL CONTROL SYSTEM**

**Implementation stage:** Optimal control system adopts Siemens S7-300 PLC and compiles the whole optimal control arithmetic with the base of modern control theory and finally is packaged into easy-use configuration module, stored in configuration module library. In configuration module library, predictive controller, state variable controller (Hua *et al.*, 2005), RBF neural network and intelligent feed-forward and other advanced control models are included, but more than 60 regular control models are also stored.

According to design scheme, we call various advanced control and normal control modes from configuration module library by configuration methods which are similar with DCS. Finally, it is the whole optimal control system of thermal units.

**Optimal control system and DCS linkage:** MODBUS communication links between optimal control system and DCS system. The coordination of optimal control system and temperature control function act as the redundancy of bumpless switchover.

To ensure reliability of optimal control system, we use security measures below.

Optimal control system sends operation state signals to DCS and once it can't get the signals, it will switch to primary Automatic Generation Control (AGC) and steam temperature control system:

- All of the analog signals sent by DCS judge its bounds and changing rates and once they are beyond the setting values, system will bumpless switchover state of AGC and steam control system
- All of the control signals sent from optimal system to DCS, like coal, feedwater flow and turbine load instructions, are limited between upper and lower bounds. DCS also is added control loop calculation control instruction bounds, according to unit condition and coal type

With the execution of measures above, troubles of optimal system would not influence the units.

**FIELD TEST EFFECT**

Number 1 700MW ultra supercritical power unit AGC and steam temperature system in a plant were put into use for the first time at 15:20 on July 2nd 2011. After debugging and improvement of cold and hot state, the



Fig. 5: The running curve of new CCS in load variation (load changing rate 9 MW/min)

system improves steady state and dynamic performances of unit coordination system and steam temperature control system obviously.

**Improvement of operation performances of coordination and reheating steam system:** Figure 5 is CCS changing load test curves. Changing load rate is set at 9MW per minute and unit load changes many times between 400 and 670 MW and maximal changing extent for a time is 100 MW. Load tracking performance is good in the process of optimal control system operation and maximal quality index of dynamic unit main steam pressure is only 0.53 MPa. Dynamic quality index of main steam temperature and intermediate point temperature is between 5 and 6.

Figure 6 is the No. 1 unit AGC operation curves at the rate of 9 MW per minute. And No. 1 unit is very stable with full AGC load limited from 400 to 650 MW. In all load disturbances of different ranges, including positive and negative changing, dynamic quality of main steam pressure is very good and intermediate point temperature, main steam temperature are all significantly better than acceptance test procedure indexes (DL/T657-2006) online of analog signal control system in the thermal power plant.

**Improvement of reheating steam temperature operation quality:** Reheating steam temperature damper control system of the primary DCS system in No.1 unit can't be switched into automation normally. It is regulated by spray desuperheating which decreases unit economy.

Figure 7 is the AGC changing load test curves at the rate of 9MW per minute. Unit load decreases from 505MW to 390MW constantly and rises to 470MW and falls to 420MW again. With large disturbance, optimized reheating steam temperature dynamic quality index is between +4 and -9°C. In the process, spray desuperheating electric actuator is closed all the time and the spray water amount is 0.

Above all, control effect and regulation qualities have been improved obviously with advanced coordination and steam temperature control system.

- Unit control regulation qualities have been improved efficiently. Changing load rate rises to 9MW per minute and regulation effect is good, as well as tracking performance. Control precision of main variable dynamic indexes is very high
- Related parameters fluctuate lightly and unit operation is stable. When changing load in large ranks at 9 MW per minute, main steam pressure never



Fig. 6: The running curve of new AGC in load variation (load changing rate 9 MW/min)

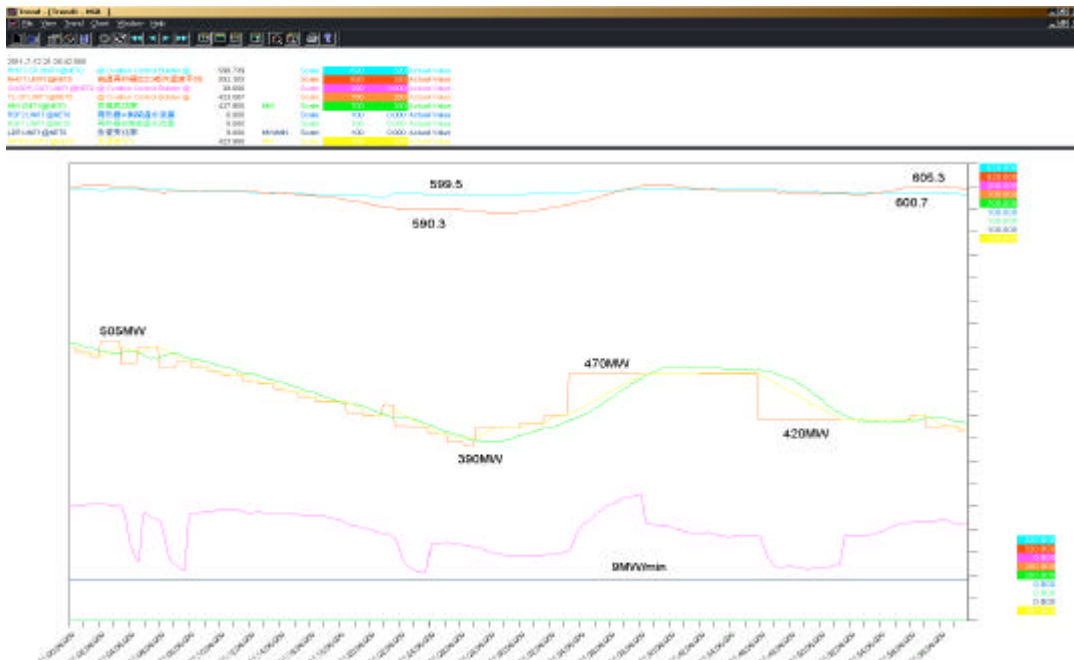


Fig. 7: The running curve of new reheat steam temperature control system (load changing rate 9 MW/min)

shocks and dynamic quality index is below 0.53 MPa. When separator temperature not fluctuates, the dynamic quality index is below 5°C. And the temperature of main steam is stable, dynamic quality index is between 5 and 8°C

- Flue gas damper regulates reheating steam temperature. In the process of stabilizing and changing load, control performance of reheating steam temperature is good. It deducts reheating spray amount and improves power plant economy



- Control system is adaptable for coal types. New control system was put into use in July, 2011. The coal quality in plants changes frequently. But control performance is not influenced by coal changing because of the good adaptation of new control system for coal type

## CONCLUSION

Optimal control system in this article, with the base of multiple advanced control techniques in modern control theories, proposes AGC coordination of large-scale thermal power units and advanced scheme of steam control. It results indicate fine quality of the new control system regulation caused by coal type changing in large-scale thermal plants.

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