MIMO Controller with Compensator via Gain tuning method for Steam Temperature Control of Thermal Power Plant

O-Shin KWON, Jin-Sung KIM, Sung-Man PARK, and Hoon HEO
Department of Control and Instrumentation Engineering, Korea University
Anam-dong, Seongbuk-gu, Seoul 136-713, KOREA

and

Won-Hee JUNG
R&D Institute Plant Control System Development Team, Doosan Heavy Industries & Construction
463-1 Jeonmin-dong, Yuseong-gu, Daejeon 305-811, KOREA

ABSTRACT

Conventional control of steam temperature using feedback cascade PID controller in the superheater and the reheater of thermal power plant is known to be efficient to compensate disturbance. However, time constant of steam temperature control of superheater and reheater is bigger than other control systems. Also, mutual interference among control loops in steam temperature control is existed. It is not easy to compensate nonlinearity and time delay due to complex and enormous structure of the thermal power plant. For the compensation of nonlinearity resulted from the complex structure of superheater and reheater, the compensator using simple mathematical model is constructed. Feedforward PID loop is designed for compensation about time delay. In order to improve performance of steam temperature control, MIMO control technique comprised with feedback/feedforward PID loop and compensator for superheater and reheater is proposed. Also gain tuning algorithm is applied to MIMO controller for more sensitive and efficient steam temperature control in various environment. In this paper, the method of gain tuning MIMO controller with compensator is implied to control the steam temperature of superheater and reheater. The simulation is implemented for 100% load steady state and 100% to 75%, 75% to 100% load changing state. The proposed gain tuning MIMO controller with compensator reveals more stable and efficient performance than conventional feedback cascade PID controller.

Keywords: Steam temperature control, Thermal power plant, MIMO controller, Gain tuning method, Nonlinearity and time delay.

1. INTRODUCTION

Thermal efficiency of turbine is increasing when temperature of generated steam goes up. Steam temperature control of boiler is essential due to complex and enormous structures of superheater and reheater in rating load state. Setpoint temperature of superheater and reheater are 569℃ and 596℃ respectively due to tube material of boiler and limitation of operation control.

Steam temperature controller maintains outlet temperatures of superheater and reheater to set point in compliance with attemperator control and balance between feed water flow and coal flow. Also, in reheater, burner tilt control is additionally implemented. However balance control between feed water flow and coal flow causes problem such as time delay in load changing state. On the other hand steam temperature control using attemperator responds relatively fast to changing of steam temperature.

Fig. 1 shows the frame of superheater for boiler typical thermal power plant, Fig. 2 shows the frame of reheater. 1st attemperator that control steam temperature is located between division superheater and platen superheater. 2nd attemperator is located between platen superheater and final superheater. In reheater, 3rd attemperator is located inlet of primary reheater.

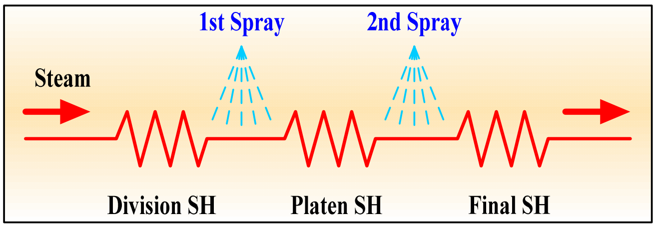

Fig. 1 The frame of superheater for a thermal power plant

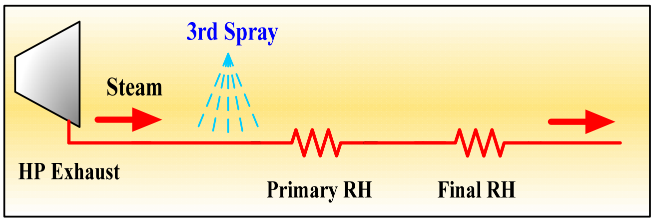

Fig. 2 The frame of reheater for a thermal power plant

In superheater, steam temperature control is comprised of platen and final superheater control. Also steam temperature control is comprised of attemperator and burner tilt control in reheater. Conventional steam temperature control is being undertaken by utilizing cascade PID controller in general. The master PID of cascade PID controller in superheater and reheater calculates and compares outlet temperature and set point. The slave PID takes delivery of calculated results from master PID. Also the slave PID calculates and compares inlet temperature and demand temperature. The attemperator takes delivery of calculated control signals from slave PID. The cascade PID controller is efficient to compensate disturbance. However, time constant of steam temperature control of superheater and reheater is bigger than other control systems. Also, mutual interference among control loops in steam temperature control is existed. It is difficult to compensate nonlinearity and time delay due to complex and enormous structure.

In order to improve nonlinearity due to complex structure of superheater and reheater, the compensator using simple mathematical model is constructed. Feedforward PID loop is designed for compensation about time delay. Also gain tuning algorithm is applied to MIMO controller for more sensitive and efficient steam temperature control in various environment.

In this paper, the construction of compensator using simple mathematical model and MIMO controller that is improved by feedback and feedforward PID loop is designed. Also, Gain tuning algorithm is applied to MIMO controller which implements steam temperature control in superheater and reheater. The proposed gain tuning MIMO controller with compensator reveals more stable and efficient performances than conventional cascade PID controller[1].

2. DESIGN OF MIMO CONTROLLER

A. Boiler model

In the boiler sections, the heat released by fuel combustion is transferred to the working fluid in the boiler. Based on this, each section of the boiler can be considered as a thermal system as shown in Fig. 3[2][4][5].

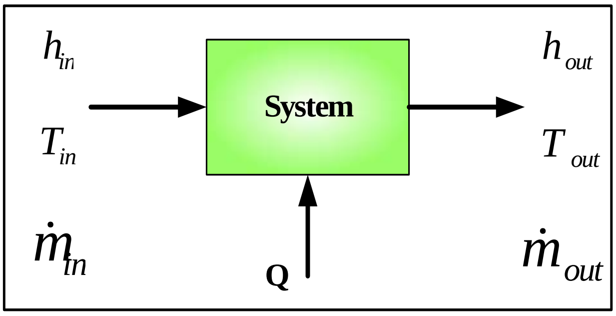

Fig. 3 Boiler subsystem

According to the global mass and energy balances we have,

$$\frac{d}{dt}\left[\rho_s \cdot V_s + \rho_w \cdot V_w\right] = \dot{m}_f - \dot{m}_s \tag{1}$$

$$\frac{d}{dt}\left[\rho_s \cdot u_s \cdot V_s + \rho_w \cdot u_w \cdot V_w + m_a \cdot C_p \cdot T_a\right] = Q + \dot{m}_f h_f - \dot{m}_s h_s \tag{2}$$

The right hand side of (2) represents the energy flow to the system from fuel and feed water and the energy flow from the system via the steam. Since the internal energy is $u = h - p/\rho$, the global energy balance can be written as

$$\frac{d}{dt}\left[\rho_s \cdot h_s \cdot V_s + \rho_w \cdot h_w \cdot V_w - pV + m_a \cdot C_p \cdot T_a\right] = Q + \dot{m}_f h_f - \dot{m}_s h_s \tag{3}$$

Multiplying (1) by h_w and subtracting the result from (3) we have,

$$\begin{aligned}(h_s - h_w)V_s \frac{d\rho_s}{dt} + \rho_s \cdot V_s \frac{dh_s}{dt} + \rho_w \cdot V_w \frac{dh_w}{dt} + \frac{d}{dt}\left[m_a \cdot C_p \cdot T_a\right] - V\frac{dp}{dt} \quad (4)\\ = Q + \dot{m}_f\left(h_w - h_f\right) - \dot{m}_s\left(h_s - h_w\right)\end{aligned}$$

It is shown that for the drum boiler, the changes in energy content of the water and metal masses are the physical phenomena that dominate the dynamics of the boiler [2]. The specific density of steam is not changing so fast, particularly in steady-state condition, to have a great effect on the model dynamics. This fact is true especially in the evaporator part where there are water and steam phases. So, these terms can be neglected with respect to other terms. Also, the last term at the left hand side of (4), V , is often neglected in modeling [17]. For simplicity, it can be taken $\dot{m}_{in} = \dot{m}_{out}$. This means that the storage of mass in the control volume is neglected. It will be shown that the effect of steam-water fraction should be considered for this part. Therefore (4) is rewritten as follows

$$\rho_w \cdot V_w \frac{dh_w}{dt} + \frac{d}{dt}\left[m_a \cdot C_p \cdot T_a\right] - V\frac{dp}{dt} = Q + \dot{m}_{in}\left(h_w - h_s\right) \tag{5}$$

This equation can be used for all subsections of the boiler as a general governing equation[2][3][6].

B. Superheater model

For modeling the superheater parts, it should be noted that only the steam phase is presented in these subsystems. Also, in once-through boilers, the pressure change is only a function of the feedwater flow rate.

Let

$$C_p = \left(\frac{\partial h}{\partial T} \right)_p , \quad C_V = \left(\frac{\partial u}{\partial T} \right)_V \tag{6}$$

where

$$\frac{dh}{dt} = \frac{\partial h}{\partial T} \frac{dT}{dt} \tag{7}$$

Then by some additional simplifications for the superheater parts, we have

$$h_s \cdot V_s \frac{d\rho_s}{dt} + \frac{d}{dt}\left[m_a \cdot C_p \cdot T_a \right] + \rho_s \cdot V_s \frac{dT_{out}}{dt} = Q + C_p \dot{m}_{in} \left(T_{in} - T_{out} \right) \tag{8}$$

The metal temperature at steady-state condition is close to the steam temperature. Also, it is shown that by removing the first two terms on the left side of (8), there is an off-set between the model response and the actual plant response at the steady-state condition. In order to make the model response close to the response of the real plant, these terms should be taking into account. Noting that the specific density is of steam approximately is constant. Therefore, we can express the second term on the left side of (8) as a function of mass flow rate.

$$\frac{d}{dt}\left[m_a \cdot C_p \cdot T_a \right] = f\left(\dot{m}_{in} \right) \tag{9}$$

It is assumed that the left side of (9) is a linear function of inlet steam flow rate.

$$f\left(\dot{m}_{in} \right) = k_a \cdot \dot{m}_{in} \tag{10}$$

The same approximation can be considered for the evaporator part. Therefore, (8) is captured as follows:

$$\frac{dT_{out}}{dt} = K_2 \left(\frac{Q}{C_p} + \dot{m}_{in} \left(T_{in} - T_{out} + B_1 \right) + B_2 \right) \tag{11}$$

where

$$K_2 = \frac{1}{\rho_s \cdot V_s}, \quad B_1 = \frac{k_a}{C_p}, \quad B_2 = k_0 \rho_s \cdot V_s \tag{12}$$

The heat supplied to the surfaces, Q can be derived from the heat transfer equations. Both convection and radiation are taken into account in the heat flow rate from combustion gas to the surfaces. It is more convenient to find a relation between the heat flow and the fuel consumption instead of combustion gas parameters. The released heat from fuel combustion can be derived as a function of fuel flow or fuel-air ratio[2][7].

The heat flow can be captured by using calorific value/lower heating value (H) of the fuel as follows:

$$Q = H \cdot \dot{m}_{fuel} \tag{13}$$

In this case, by considering $K_1 = H / C_p$, the superheater model is derived as equation (14);

$$\frac{dT_{out}}{dt} = K_2 \left(K_1 \dot{m}_{fuel} + \dot{m}_{in} \left(T_{in} - T_{out} + B_1 \right) + B_2 \right) \tag{14}$$

C. Attemperator model

The superheater and reheater temperatures must be kept constant at specific temperature. The attemperator is implemented between these sections to control outlet temperature. Furthermore, de-superheating spray is used to achieve mixing between the superheated steams at the outlet of the preceding component (e.g., the primary superheater). The water spray is modulated by suitable valves. Because the attemperator has a relatively small volume, the mass storage inside that is negligible. Therefore, the steady-state mass and energy balances yield.

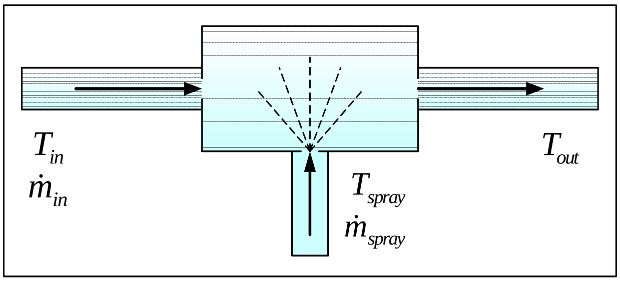

Fig. 4 Attemperator

$$\dot{m}_{in} + \dot{m}_{spray} = \dot{m}_{out} \tag{15}$$

$$\dot{m}_{in} h_{in} + \dot{m}_{spray} h_{spray} = \dot{m}_{out} h_{out} \tag{16}$$

During a normal operation, steam flow _min in the secondary superheater is imposed (over a wide band) by the load controller, the specific enthalpy h_{in} is determined by upstream superheater and h_{spray} is nearly constant. The inlet temperature of the second superheater, T_{out} is governed by the following (14):

$$\dot{T}_{out} = \frac{1}{C_p} \Delta h_{out} = \frac{\left(\overline{h}_{in} - \overline{h}_{out} \right)}{C_p \overline{m}_{out}} \dot{m}_{out} + \frac{\overline{m}_{in}}{\overline{m}_{out}} \dot{T}_{in} - \frac{\left(\overline{h}_{in} - \overline{h}_{spray} \right)}{C_p \overline{m}_{out}} \dot{m}_{spray} \tag{17}$$

This equation yields an accurate attemperator temperature model. However, a simple model can be used instead of this equation based on thermal balance formula as follows[2][4]:

$$T_{out} = \frac{\dot{m}_{in} T_{in} + \dot{m}_{spray} T_{spray}}{\dot{m}_{in} + \dot{m}_{out}} \tag{18}$$

D. Superheater

Fig. 5 shows the frame of MIMO controller that is applied compensator and feedback/feedforward loop PID controller in superheater.

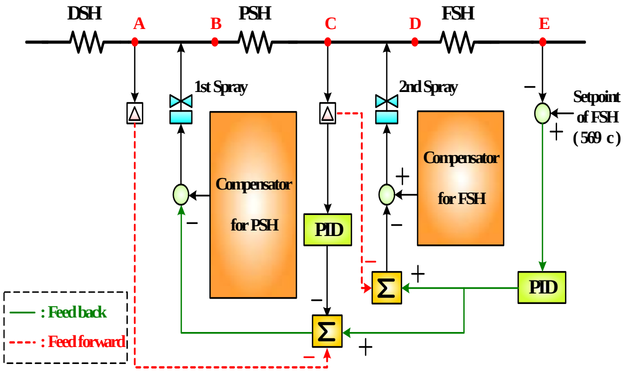

Fig. 5 The frame of MIMO controller for superheater

In superheater, steam temperature control is comprised of platen and final superheater control. The feedback signal is utilized outlet temperatures of each superheater. The feedforward signal of predictive control structure is utilized outlet temperatures of previous superheaters(division and platen superheater). Also, compensators of each superheater can be formulated as (20) and (21) using superheater and attemperator model as (14) and (18).

It is assumed that

$$\dot{m}_A \approx \dot{m}_C \cong \dot{m}_{MST} \tag{19}$$

$$\frac{d}{dt}\dot{m}_{spray1} = \frac{d^2}{dt^2}T_C - \frac{d}{dt}T_A + \frac{d}{dt}T_C - \frac{d}{dt}\dot{m}_{fuel} - \frac{d}{dt}\dot{m}_{MST} \tag{20}$$

$$\frac{d}{dt}\dot{m}_{spray2} = \frac{d^2}{dt^2}T_E - \frac{d}{dt}T_C + \frac{d}{dt}T_E - \frac{d}{dt}\dot{m}_{fuel} - \frac{d}{dt}\dot{m}_{MST} - \frac{d}{dt}\dot{m}_{spray1} \tag{21}$$

(20) is the compensator model equation of platen superheater, (21) is the compensator model equation of final superheater. The calculated spray valve changing value by (20) and (21) is compensated to feedback and feeforward loop PID result, then the final output controls flow of spray water.

E. Reheater

Fig. 6 shows MIMO controller that controls attemperator and burner tilt for efficient steam temperature control in reheater. The structure of MIMO controller is comprised of feedback/feedforward loop PID control and compensator such as superheater controller.

In reheater, steam temperature control is comprised of attemperator and burner tilt control. The feedback signal is utilized outlet temperatures of final reheater outlet temperature. The feedforward signal of predictive control structure is utilized outlet steam temperature of HP turbine. Also, compensator of reheater can be formulated as (23) using superheater and attemperator model as (14) and (18).

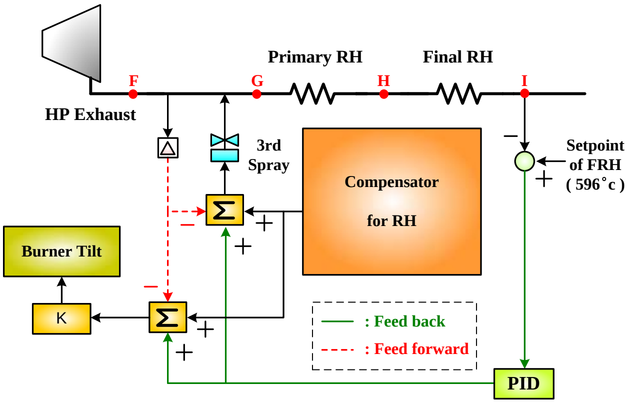

Fig. 6 The frame of MIMO controller for reheater

It is assumed that

$$\dot{m}_F \cong \dot{m}_{MST} \tag{22}$$

$$\frac{d}{dt}\dot{m}_{spray3} = \frac{d^2}{dt^2}T_I + \frac{d^2}{dt^2}T_H - \frac{d}{dt}T_F - \frac{d}{dt}\dot{m}_{fuel} - \frac{d}{dt}\dot{m}_{MST} \tag{23}$$

The calculated spray valve changing value by (23) is compensated to feedback and feedforward loop PID result, then the final output controls flow of spray water. The burner tilt is changed smaller than changing value of spray valve via scaling factor K for unstable of heat balance in boiler.

3. GAIN TUNING ALGORITHM

Fig. 7 shows the concept of Anti-reset windup algorithm.

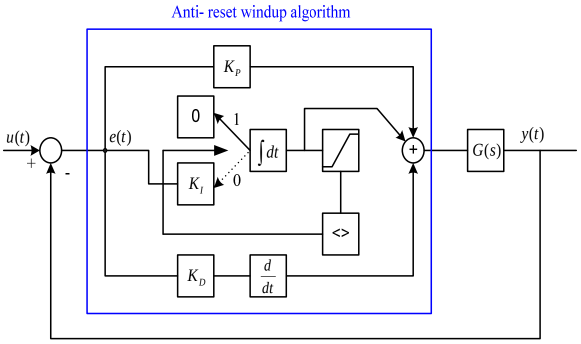

Fig. 7 The Concept of Anti-reset windup

The integrator about error in PID controller remove very little remained deviation for stable control performance. However, the settling time is too late due to generate time delay to control output signal when enormous error is generated by irregular disturbance and nonlinearity in systems. In this case, control performance is declined[8].

Therefore integral coefficient reset to '0' then control performance is minimized effect of enormous and irregular error when integration value of the error signal exceeds boundary function such as Fig. 7.

Anti-reset windup algorithm can be control properly according to characteristic of system. Also the algorithm is simple gain tuning algorithm is not involved special model or computation skill.

4. DESIGN OF GAIN TUNING MIMO CONTROLLER AND SIMULATION

A. Design of Gain tuning MIMO controller

Fig. 8 shows the frame of gain tuning MIMO controller that is applied gain tuning algorithm to designed MIMO controller in superheater and reheater as are in Fig. 5 and 6.

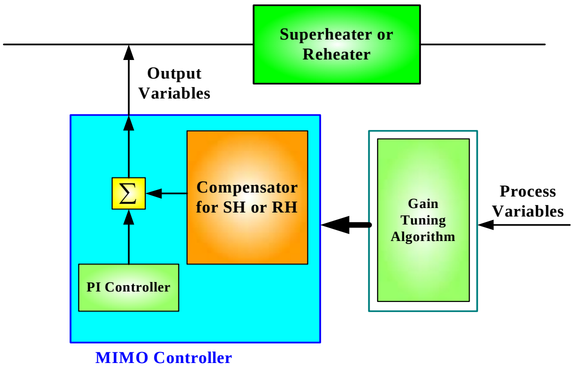

Fig. 8 The frame of Gain tuning MIMO controller

TABLE I
PROCESS VARIABLES

<table>
<tr><th colspan="3">Process variables</th></tr>
<tr><th></th><th>Superheater</th><th>Reheater</th></tr>
<tr><td rowspan="2">Input Variables</td><td>DSH outlet temperature
PSH outlet temperature
FSH outlet temperature</td><td>PRH outlet temperature
FRH outlet temperature</td></tr>
<tr><td colspan="2">Main steam & Coal flow</td></tr>
<tr><td>Output Variables</td><td>1st spray valve
2nd spray valve</td><td>3rd spray valve
Burner tilt</td></tr>
</table>

In Table I, process variables are utilized tuning variables that are computed gain tuning or control variables. The gain tuning is decided according to verification of control performance of MIMO controller in superheater and reheater. In order to tune the gain, boundary function is set through characteristic of the system.

B. Simulation

The supposed gain tuning MIMO controller is verified using simulator is realized by typical thermal power plant. The simulation is implemented for 100% load steady state and 100% to 75% or 75% to 100% load changing state.

Fig. 9 and Fig. 10 show performances of cascade PID controller and gain tuning MIMO controller for 100% load steady state. Fig. 9 shows performance of gain tuning MIMO controller in superheater. The result shows stable control performance that there is deviation of temperature about 0.05℃.

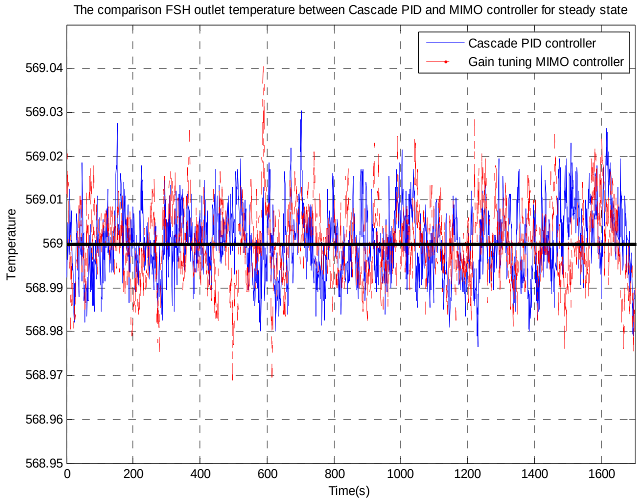

Fig. 9 The performances of Cascade PID and gain tuning MIMO controller for load steady state in superheater

Fig. 10 shows system responses under gain tuning MIMO controller in reheater. The result shows stable control performance that there is deviation of temperature about 0.1℃.

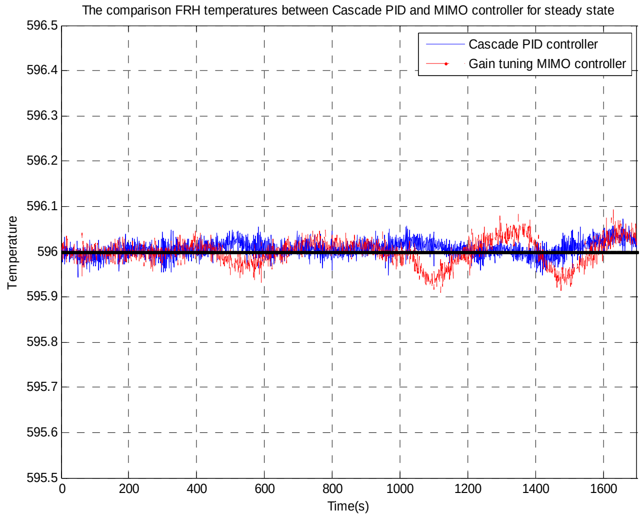

Fig. 10 The performances of Cascade PID and gain tuning MIMO controller for load steady state in reheater

Fig. 11 and Fig. 12 show system performances of cascade PID controller and gain tuning MIMO controller for 100% to 75% and 75% to 100% load changing state. Fig. 9 shows performance of gain tuning MIMO controller in superheater. The result shows stable control performance that there is deviation of temperature about 0.05℃.

The load changing state appears green line. The load state maintains 100% load steady state for 60s in first, decreases to 75% load state from 60s to 560s. Since then, the load state maintains 75% for 600sec, increases to 100% load state from 1160s to 1560s, and then maintains 100% load steady state for 140sec.

The performance of gain tuning MIMO controller in superheater along with load changing sequence is shown in Fig.11. The result shows improved performance compared with cascade PID controller as 20%. Especially, in 75% load steady state, the result shows 60% of improved control performance as deviation of temperature about 0.6℃ compared with cascade PID controller has deviation of temperature about 1.5℃.

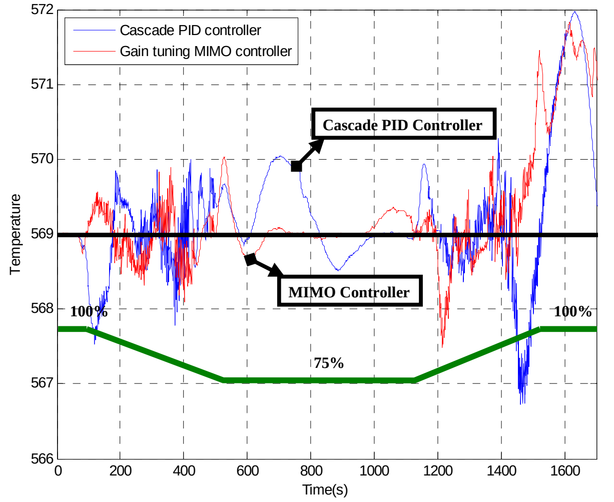

Fig. 11 The performances of Cascade PID and gain tuning MIMO controller for load changing state in superheater

Fig. 12 shows the system response under gain tuning MIMO controller in reheater. The result shows 10% of improved control performance as deviation of temperature about 9℃ compared with cascade PID controller has deviation of temperature about 10℃.

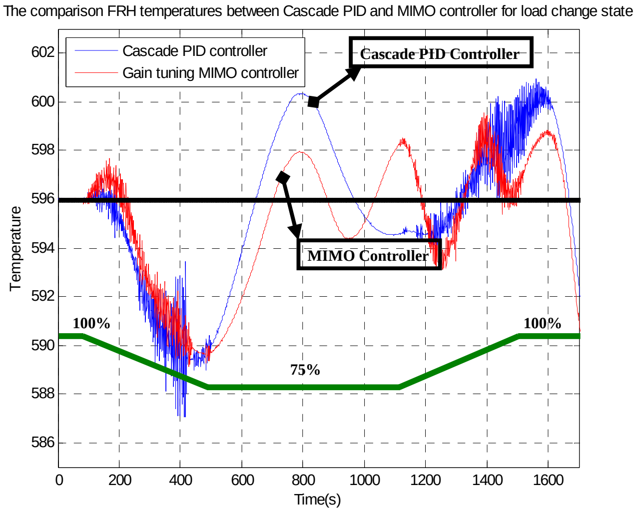

Fig. 12 The performances of Cascade PID and gain tuning MIMO controller for load changing state in reheater

5. CONCLUSION

Generally, the control of steam temperature using cascade PID controller is known to be effective for disturbance compensation in thermal power plant. However, it is essential to compensate nonlinearity and time delay due to complex and enormous structure of superheater and reheater. In this paper, the compensator using simple mathematical model is designed taking into account the nonlinearity and time delay. The integrated feedback and feedforward loop PID control scheme is applied. Also the gain tuning algorithm based on anti-reset windup method is applied to MIMO controller for sensitive and efficient steam temperature control in various environments, even in load changing state. Improved control performance for 100% load steady state and 100% to 75%, 75% to 100% load changing states are revealed respectively from Fig.8 through Fig.11 using simulator for typical thermal power plant.

As a further study, more accurate modeling of superheater and reheater should be undertaken for better performance of compensator. Also, the study of parameter tuning method in superheater or reheater under various varying environments is indispensable for more stable control.

6. ACKNOWLEDGMENT

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