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SUPERHEATED STEAM TEMPERATURE CONTROL FOR BOILER USING ADAPTIVE DYNAMIC FEEDFORWARD COMPENSATORS

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Abstract. This paper proposes a new control strategy for improving the performance of the superheated steam temperature control system in thermal power plants. Based on the analysis of the limitations of the static feedforward compensators (SFC) for temperature and boiler load disturbances in the existing control system of the auxiliary boiler in Dung Quat refinery, two adaptive dynamic feedforward compensators (ADFC) for temperature and boiler load disturbances were proposed to replace the SFCs. In addition, a method for predicting the tube wall temperature of the superheater using an autoregressive moving average (ARMA) model was also proposed. The simulation results for the two typical cases of the boiler load change indicate that the control system incorporated with the proposed ADFCs improves significantly the performance of the control system.

Keywords: superheated steam temperature control; thermal power plant; adaptive dynamic feedforward compensator, autoregressive moving average.

Classification numbers: 4.10.4; 5.4.2

1. INTRODUCTION

Steam temperature control of a superheater is critical for the safe, reliabile and efficient operation of a power plant boiler. The desired deviation range of the outlet superheated steam temperature is generally ± 5 ^{o}C from the setpoint. Operating at temperatures outside this range can seriously affect the safety and economics of the boiler and turbine operation. Challenges in controlling steam temperature of superheaters are that the model's nonlinearity, long transportation delay by the steam flow through the superheater tube, and disturbances from changes in power load, the heat flow from the flue gas and the steam temperature from the previous superheater [1, 2]. Therefore, the issue of improving the performance of the superheated steam temperature control system in power plants has attracted very considerable interest and attention of researchers. Many control strategies have been proposed over decades such as an adaptive sliding mode and fuzzy gain scheduling mothod [2], prediction-based control methods [3, 4], optimal control strategy for minimization of energy destruction [5], inverse dynamic neuro control technique [6], etc. However, in addition to the gain scheduling method, the remain control techniques are complex and difficult to the existing boiler control system that integrates distributed control system or industrial process control system.

The superheated steam temperature control system in Dung Quat refinery utilizes cascade PI controllers incorporated with static feedforward compensators (SFC) to regulate the main steam temperature to the target value as shown in Figure 1. The outlet steam temperature of the second superheater, T_{ho2}, is measured and provided as the process variable to the master loop PI controller TIC-04. The control output signal of TIC-04 is added to the feedforward signal computed from the dynamic temperature variation static compensator FY-03B, the result of the summation block TY-4 is the feedforward to the inner loop PI controller TIC-12A. Superheated steam temperature after desuperheater is sensed and provided as the process variable to the inner loop PI controller TIC-12A. The control output signal of TIC-12A is added to the feedforward signal generated from the load variation static compensator FY-03A to control the water spray valve position TV-12. The two SFCs (YF-03B and FY-03A) were fine-tuned during the boiler start up based on the boiler combustion tests at 25 %, 50 %, 75 %, and 100 % of the static power load. In addition, to avoid humidity in the steam system network, the superheated steam temperature after desuperheater is also controlled by PI controller TIC-12B using saturated steam temperature plus 10 ^oC as the minimum temperature permissible in the steam flow into the second superheater. The outputs of both controllers TIC-12A and TIC-12B are compared in the low signal selector and the lowest of the two signals is used for correcting the position of the water spray valve.

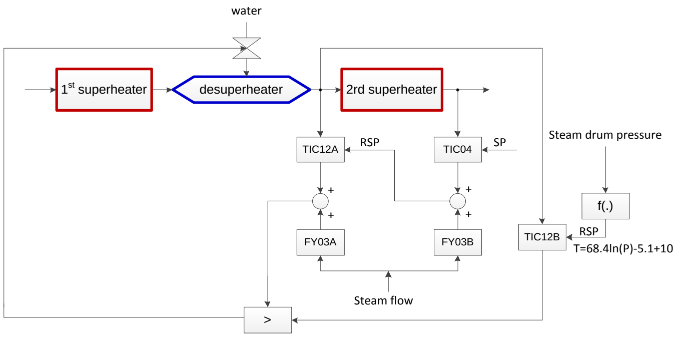

Figure 1. Superheated steam temperature control system in Dung Quat refinery.

This control configuration has many advantages like – it is not complicated, simple to tune and easy to operate; the process of turning controllers is simple and easy to operate. When the boiler load changes slowly, it is easy to maintain the outlet superheated steam temperature around the desired value (505 ^oC) with the deviation range does not exceed ± 5 ^0C. However, there are some drawbacks of this control configuration, that are: (i) The response speed of the control system to changes in the heat flow from the flue gas and boiler load is low therefore the time that devices operate under high temperature lasting from 10 to 20 minutes; (ii) When the boiler load changes quickly, the outlet superheated steam temperature exceeds the desired deviation range (± 5 ^oC) with the maximum deviation up to 15.5 ^oC and lasts about 20 minutes as shown in Figure 2. The reason is that when the boiler load changes dramatically, due to the thermal inertia of the boiler, the rate change of steam flow is slower than that of the heat in the combustion chamber. Therfore, the heat absorbed by superheaters (Q_h) varies faster than the steam flow rate (m_h) through the superheater tubes, which leads to significant change in the outlet steam temperature. Since, the both SFCs (FY-03A and FY-03B) were not designed for dynamic compensation, so that they are not effective when the boiler load changes rapidly.

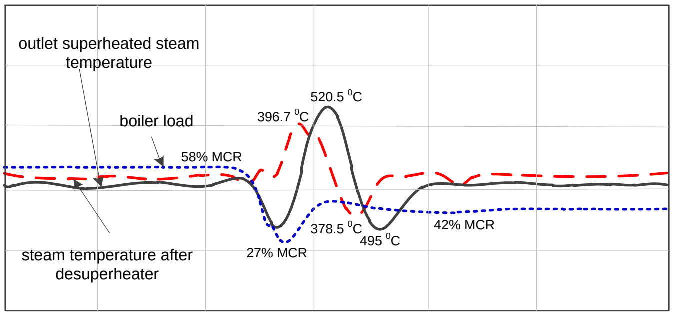

Figure 2. Variations of temperature when the boiler load decreases from 58 % to 27 % then increases to 42 % with 10 % MCR ramp rate.

In order to overcome the above limitations of the existing control technique, in this paper the authors propose adaptive dynamic feedforward compensators (ADFC) with simple and easy to apply algorithm that can directly integrate into the existing temperature control system of most today's boiles in the industry. The proposed ADFCs incorporated with the existing cascade PI controllers was applied to control the superheated steam temperature for the 196 t/h oil/gas-fire boiler with the steam pressure of 10.7 MPa and the desired outlet superheated steam temperature of 505 ^{o}C in Dung Quat refinery.

2. PROPOSED ADAPTIVE DYNAMIC FEEDFORWARD COMPENSATORS

The idea is to replace two SFCs (FY-03A and FY-03B) in the control configuration in Figure 1 with two ADFCs (DFF1 and DFF2) as shown in Figure 3 to reject the two main disturbances in the system: boiler load disturbance (steam flow in the superheaters) and heat disturbance (heat flux from flue gas). Where, DFF1 is the load disturbance compensator that is designed based on the principle of heat and mass balance of the steam flowing in and out of the desuperheater. Thus, the mass flow rate of water ($\dot{m}_n$) to be sprayed into the steam flow (corresponding to the valve position, v_p) can be calculated in advance to compensate the enthanpy of the steam flow before going into the second superheater. Therefore, the effect of the outlet steam temperature (T_{ho1}) and steam flow rate ($\dot{m}_{h1}$) from the first superheater on the outlet steam temperature (T_{ho2}) of the second superheater can be reduced significantly.

Meanwhile, DFF2 is the heat disturbance compensator that was designed to compensate against variations in the heat flux from the flue gas (Q_k). However, instead of constructing a model for dicrect estimation of Q_k that is very complex and uncertain due to the dust deposition on the furnance as well as tube walls continuously alter the heat transport situation [7], this paper proposed an estimation model for the tube temperature (T_p) that presents Q_k by using measured values of the steam temperature at input and output of the superheaters in the past and present. The output signal of DFF2 ($T_{hi2}^{FF}(t)$) is the set point value for the inner loop PI controller TIC-12A and $T_{hi2}^{FF}(t)$ is dertermined based on the target outlet temperature of the second superheater

($T_{ho2}^{sp}(t)$) and estimated tube temperatures at the present ($\hat{T}_p(t)$) and in the future ($\hat{T}_p(t+d_h)$), where d_h is the transportation time of the steam in the superheater. Because d_h will change when the boiler load changes, in this work an adaptive autoregressive moving average (ARMA) model to predict $\hat{T}_p(t+d_h)$ is proposed.

2.1. Compensator design (ADFC)

2.1.1. Assumptions

The temperature balance equations for the steam flow in the superheaters are based on the following assumptions:

- The inlet and outlet pressures of the superheaters are the same and do not change over time. In fact, the difference between the inlet pressure and outlet pressure is about 3 % [8].
- The tube temperature T_p is uniformly distributed along the diameter direction, i.e., $\partial T_p / \partial r = 0$ [3].
- The heat-transfer efficiency of the tube bank is the same.
- The water sprays into the desuperheater immediately vaporized and well mixed with the steam flow.

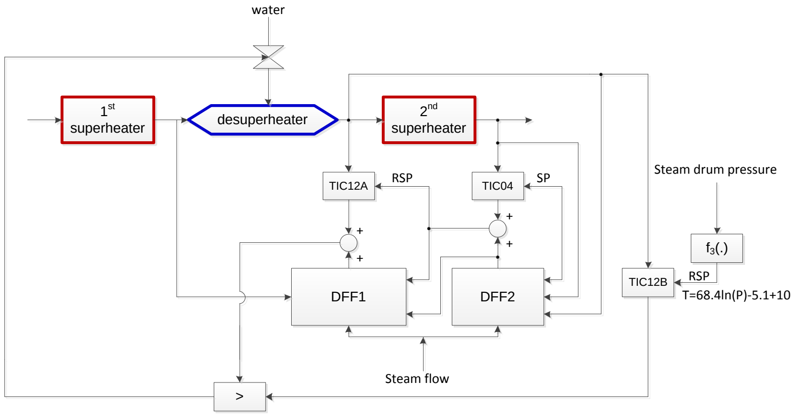

Figure 3. Superheated steam temperature control system with proposed ADFCs.

2.1.2. Design adaptive dynamic feedforward compensator against variations in Q_k (DFF2)

Based on the above assumptions, the heat balance equation of the steam flow in the superheater with reference to the notations in Figure 4 is written as follows:

$$\pi R_i^2 \rho_h \partial x C_h \partial T_h(x,t) + \pi R_i^2 \rho_h C_h u_h \partial T_h(x,t) \partial t = \pi 2 R_i \alpha_h \left[T_p - T_h(x,t)\right] \partial x \partial t \quad (1)$$

where, T_p is the tube wall temperature, $T_h(x,t)$ is the steam temperature distributed in the tube, R_i is the inner radius of the tube, u_h is the linear velocity of the steam, ρ_h is the density of steam, C_h is the specific heat at constant pressure, and α_h is the heat transfer coefficient between the tube wall and the steam.

Devide both sides of (1) by $\partial x \partial t$, we obtain

$$\frac{\partial T_h(x,t)}{\partial t}+u_h\frac{\partial T_h(x,t)}{\partial x}=\beta_h\left(T_p-T_h(x,t)\right),\quad \text{where } \beta_h=\frac{2\alpha_h}{R_i\rho_h C_h} \tag{2}$$

with the initial condition $T(x,0) = 0$ and boundary conditions $T(0,t)=T_{hi2}$, $T(L_p,t)=T_{ho2}$. Taking the Laplace transform on (2) yields

$$\frac{\partial T(x,s)}{\partial x}+\frac{s+\beta_h}{u_h}T(x,s)=\frac{\beta_h}{u_h}T_p(s). \tag{3}$$

Solving equation (3), we obtain the solution

$$T(x,s)=e^{-(s+\beta_h)\frac{x}{u_h}}\left(\frac{\beta}{s+\beta}e^{(s+\beta_h)\frac{x}{u_h}}T_p(s)+C\right). \tag{4}$$

Substitute $T(0,s)=T_{hi2}(s)$ and $T(L,s)=T_{ho2}(s)$ into (4) and rearranging the result equation, the outlet temperature of the second superheater is finally obtained as

$$T_{ho2}(t)=e^{-\beta_h d_h}T_{hi2}(t-d_h)+\frac{\beta_h}{s+\beta_h}\left(T_p(t)-e^{-\beta_h d_h}T_p(t-d_h)\right). \tag{5}$$

where $d_h=\dfrac{L_p}{u_h}$ is the transportation time of the steam in the second superheater and L_p is the length of the second superheater.

Based on (5), replace T_{ho2} by its setpoint value T_{ho2}^{sp} and $T_p(t)$ by its estimated value $\hat{T}_p(t)$ we have:

$$T_{hi2}^{FF}(t)=e^{\beta_h d_h}T_{ho2}^{sp}(t+d_h)-\frac{\beta_h}{s+\beta_h}\left[e^{\beta_h d_h}\hat{T}_p(t+d_h)-\hat{T}_p(t)\right]. \tag{6}$$

where, $T_{ho2}^{sp}(t+d_h)$ is the setpoint of the outlet temperature of the second superheater at d_h seconds ahead. The estimated pipe temperature is calculated as

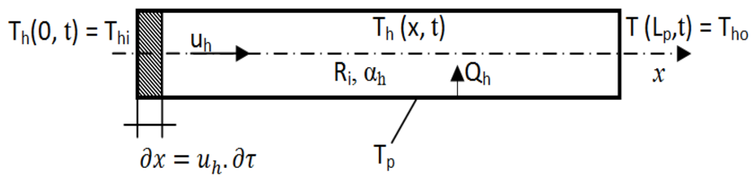

Figure 4. Variables of the steam flow in the superheater tube.

$$\hat{T}_p(t)=e^{-\beta_h d_h}\hat{T}(t-d_h)+\left(\frac{1}{\beta_h}\frac{d}{dt}+1\right)\left[T_{ho2}(t)-e^{-\beta_h d_h}T_{hi2}(t-d_h)\right]. \tag{7}$$

where, $\hat{T}_p(t+d_h)$ is the predicted tube temperature at d_h seconds ahead. Because d_h is inversely proportional to the flow rate of the steam in the superheater (i.e., boiler load) and the boiler load can change during operation, therefore $\hat{T}_p(t+d_h)$ should be predicted adaptively with changes in the boiler load. This paper proposed a prediction method based on an ARMA model with five levels corresponding to five operating points of the boiler load that are 20 %, 40 %, 60 %, 80 % và 100 % MCR as described in Figure 5, in which d_i, $I = 1÷5$ are the prediction time periods corresponding to the above boiler loads. In this work, the estimation ARMA model is simplified by assuming that there is no effect of exogenous variables (for example, environment temperature) to the tube wall temperature. Also, the disturbances are assumed to have little effect on the tube wall temperature.

By defining a membership function $f(x)$ as shown in Figure 5, for an arbitrary load (m_h) between 20 % and 100 %, the predicted value $\hat{T}_p(t+d_h)$ can be obtained by linear interpolation from two predicted values of two closest prediction models.

$$\hat{T}_p(t+d_h) = \alpha_i \hat{T}_p(t+d_i) + \alpha_{i+1} \hat{T}_p(t+d_{i+1}) \text{ with } \alpha_i + \alpha_{i+1} = 1 \ . \tag{8}$$

In summary, the procedures to calculate the feedforward signal that compensate variations in Q_k are as follows:

1. Estimate the tube temperature $\hat{T}_p(t)$ as equation (7);
2. Calculate the predicted value $\hat{T}_p(t+d_h)$ as equation (8);
3. Calculate the desired temperature of the inlet water steam $T_{hi2}^{FF}(t)$ of the second superheater as equation (6).

2.1.3. Design adaptive dynamic feedforward compensator against variations in m_h (DFF1)

Figure 6 shows the desuperheater with the associated thermal and mass variables, where h and $\dot{m}$ denote the enthalpy and mass flow rate, respectively.

Equations of steady state mass and enthalpy balances around the desuperheater are described as follows:

$$\dot{m}_{h1} + \dot{m}_n = \dot{m}_{h2} \, . \tag{9}$$

$$\dot{m}_{h1} h_{o1} + \dot{m}_n h_n = \dot{m}_{h_2} h_{i2} \, . \tag{10}$$

From (9) and (10), we obtain

$$\dot{m}_n = \frac{h_{o1} - h_{i2}}{h_{o1} - h_n} \dot{m}_{h2} \, . \tag{11}$$

Because $h_{i2} = h_{i2}^{sp} = f(T_{hi2}^{sp})$ is the target enthalpy of the outlet steam of the desuperheater, therefore, the mass flow rate of water needed to spray into the desuperheater can be rewritten as

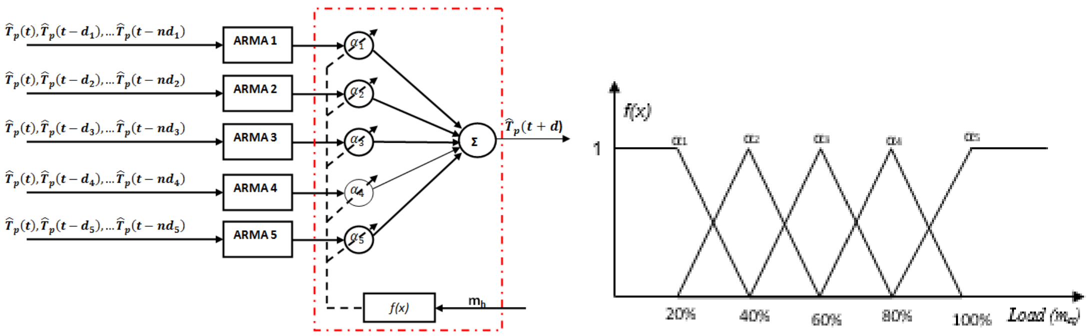

Figure 5. Prediction of the tube wall temperature based on the ARMA model.

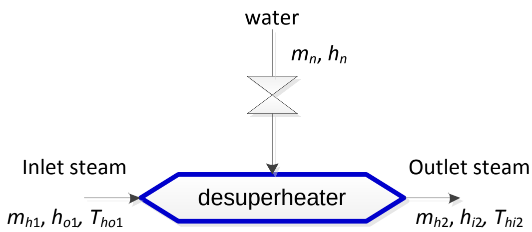

Figure 6. Thermal and mass variables around the desuperheater.

$$\dot{m}_n = \frac{h_{o1} - h_{i2}^{sp}}{h_{o1} - h_n} \dot{m}_{h2} . \tag{12}$$

The control valve can be modeled as a first-order linear dynamic system, therefore $\dot{m}_n$ also can be calculated as follows.

$$\dot{m}_n = vp^{FF} \lim_{s \to 0} \left(\frac{K_v}{\tau_v s + 1} \right) = vp^{FF} K_v . \tag{13}$$

where vp^{FF} is the valve position in percentage of opening and K_v = 0.05 kg/s per percentage of opening [8]. Finally, we have

$$vp^{FF} = \frac{\dot{m}_n}{K_v} . \tag{14}$$

In summary, the procedures to calculate the feedforward signal that compensate variations in m_h are as follows

1. Calculate the enthalpy of the inlet and outlet stream of the desuperheater (look up table) [10];
2. Calculate the mass flow rate of water as equation (12);
3. Calculate the percentage of opening of the valve position as equation (14).

3. SIMULATION RESULTS

To simulate and verify the effectiveness of the proposed control system, the model of the superheated system and its parameters as presented in the author's work [9] was used. Figure 7 shows the performance of the tube wall temperature predictor. It can be seen that when the boiler load changes between 40 % MCR and 100 % MCR, the prediction error is less than 0.5 ^{o}C.

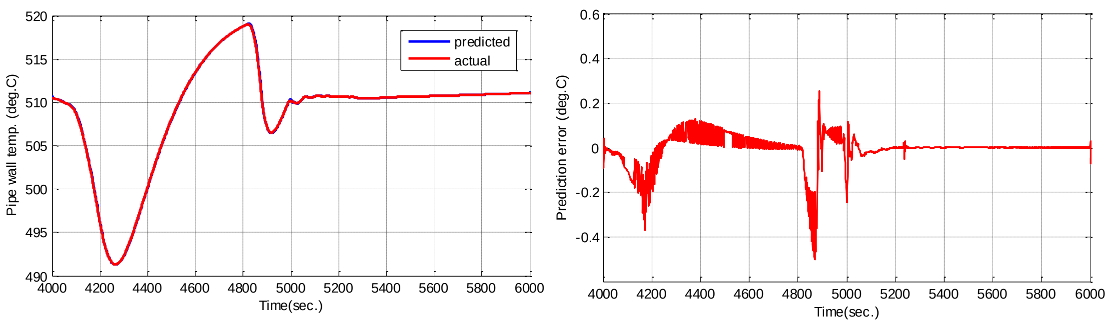

Figure 7. Comparison of the predicted and actual values of the tube wall temperature.

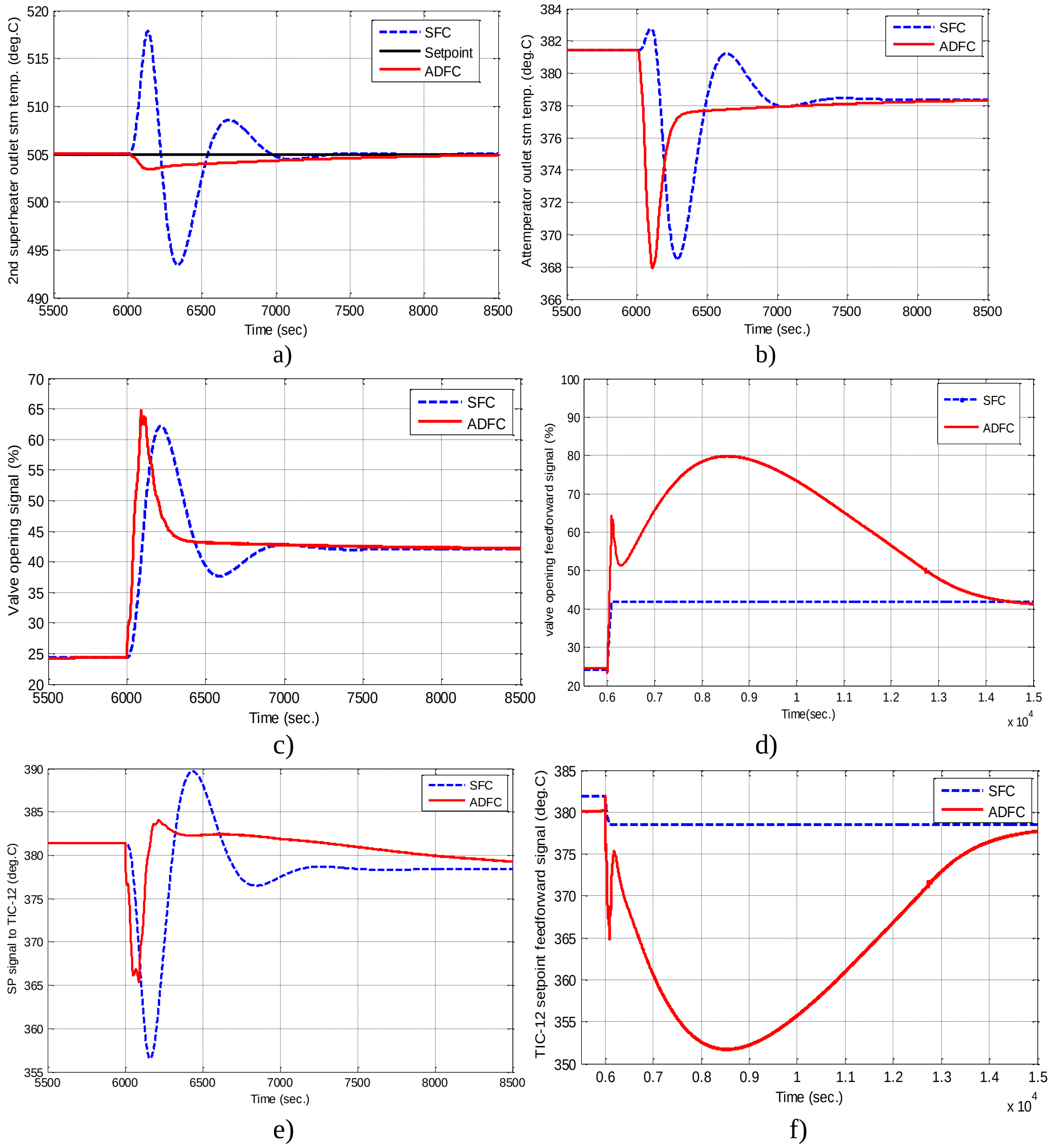

Figure 8. When the boiler load increase from 60 % MCR to 90 % MCR: a) outlet temperature of the second superheater, b) outlet temperature of the desuperheater, c) the control signal to the control valve, d) the feedforward signal for load disturbance compensation, e) the setpoint signal leading to the iner loop controller TIC-12, and f) the feedforward signal for heat disturbance compensation.

The performance of the superheated control system incoporated with the proposed adaptive dynamic feedforward compensators were compared with that of the existing superheated control system (i.e., use static feedforward compensators) for following cases:

Boiler load increase: This is the most common case in the operation of a boiler, for example when a boiler is experiencing an emergency stop, the remaining boilers must automatically increase the load to compensate for this shortage. The simulation results when the boiler load increase from 60 % MCR to 90 % MCR are shown in Figure 8. As shown in Figure 8(a), the control system with ADFCs clearly enhance the control performance, the maximum derivation of temperature is less than 1.5 ^{0}C while that is up to 12.8 ^{0}C with SFCs. Figure 8(b) shows that the response of outlet temperature of the desuperheater with SFCs is more delay than that with ADFCs about 140 s although the feedforward signals lead to the control valve of both ADFCs and SFCs are almost at the same time (Figure 8(c)). This is because the feedforward signal for load disturbance compensation from SFC (FY-03A) is calculated at the steady state, which is constant during the transient process and is approximately 42 % (Figure 8 (d)). Also, the feedforward signal for temperature disturbance compensation from SFC (FY-03B) that leads to the iner loop controller TIC-12 remains almost constant during the transient process (Figure 8(f)). Meanwhile, the feedforward signal from ADFC (DFF2) is calculated based on the thermodynamic variables of the superheater, therefore, the signal amplitude decreases from 382 ^{o}C to 352 ^{o}C and then gradually increases the steady value of 378 ^{o}C (Figure 8(f)). With both ADFCs (DFF1 and DFF2), the setpoint signal leading to the iner loop controller TIC-12 (Figure 8(e)) and the signal leading to the control valve (Figure 8(c)) are quickly generated, and their amplitudes are adaptively varied with the thermodynamic process orcurring in the superheaters, therefore, the disturbances in boiler load and in heat during the boiler load increase can be significantly compensated.

Boiler load decrease: This case happens when devices using steam experience an emergency stop or problems occuring in the steam network, that leads to a dramatical drop in the boiler load. At that time, the boiler is required to rapidly reduce the power to ensure that the over-pressure does not occur in the piping system and in related devices. As a result, the temperature in superheaters will change drastically. The simulation results when the boiler load decreases from 70 % MCR to 50 % MCR are shown in Figure 9. It can be seen from Figure 9(a) that the maximum deviation of the outlet temperature of the second superheater is less than 1.2 ^{o}C with ADFCs while that is about 10.1 ^{o}C with SFCs although the feedforward signals lead to the control valve of both ADFCs and SFCs are almost the same (Figure 9(b)).

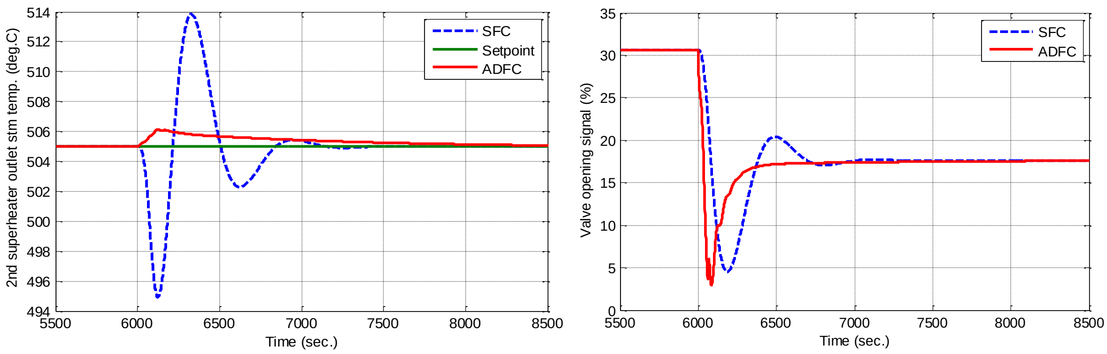

Figure 9. When the boiler load descreases from 70 % MCR to 50 % MCR: a) the outlet temperature of the second superheater and b) the control signal to the control valve.

4. CONCLUSIONS

This paper proposed ADFCs incorporated with the existing superheated control system for the thermal power plant in the Dung Quat refinery. The simulation results for the two typical cases that often occur during the operation of the boiler show that the performance of the control system with the proposed ADFCs enhance significantly compared with the existing SFCs. For both two operation cases, the deviations of the outlet temperature of the second superheater with ADFCs are in the desired range (± 5 ^{o}C). As a result, the control system with the proposed ADFCs can be utilized to reduce the risk of overheating, improve the safety, reliability and efficience of boilers in thermal power plants.

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