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Temperature Control of Ultrasupercritical Once-through Boiler–turbine System Using Multi-input Multi-output Dynamic Matrix Control

Un-Chul Moon† and Woohun Kim*

Abstract – Multi-input multi-output (MIMO) dynamic matrix control (DMC) technique is applied to control steam temperatures in a large-scale ultrasupercritical once-through boiler–turbine system. Specifically, four output variables (i.e., outlet temperatures of platen superheater, finish superheater, primary reheater, and finish reheater) are controlled using four input variables (i.e., two spray valves, bypass valve, and damper). The step-response matrix for the MIMO DMC is constructed using the four input and the four output variables. Online optimization is performed for the MIMO DMC using the model predictive control technique. The MIMO DMC controller is implemented in a full-scope power plant simulator with satisfactory performance.

Keywords: Multi-input multi-output (MIMO) dynamic matrix control (DMC), Model predictive control (MPC), Boiler–turbine system, Once-through boiler, Ultra supercritical boiler (USC)

1. Introduction

Compared with drum-type boiler, once-through boiler has less metal weight and higher working velocity in steam power plants [1]. The requirements for environmental protection and high efficiency have resulted in supercritical and ultrasupercritical (USC) once-through boilers that have efficient heat-exchange cycles in high steam temperature and pressure [2], [3].

From the view point of automatic control, however, dynamics of large-scale once-through boiler system contains many dead zones, actuator saturations, and uncertainties. To overcome these problems, different kinds of control have been developed [4]–[7].

In industrial practice, the proportional–integral–derivative (PID) control scheme remains the most widely used of all controllers. This scheme provides a simple structure and stabilized performance, and is most familiar to field engineers. However, this controller has weakness in that, in terms of multi-input multi-output (MIMO) system, it cannot provide a satisfactory performance because of its monotonous control mechanism [8], [9].

To overcome this weakness, model predictive control (MPC) has been used. MPC refers to a class of control algorithms that compute a sequence of control inputs based on an explicit prediction of outputs within a future time horizon [10]. One of the most well-known MPC algorithms for the process control is dynamic matrix control (DMC), which assumes a step-response model for the underlying system. Multivariable DMC has been discussed extensively [11]–[14]. DMC has been successfully applied to numerous industrial processes, and many commercial softwares have been developed (e.g., DMC+, SMC, RMPCT, HIECON, PFC, OPC, and so on).

Driven by these successes in the commercial sector, attempts have been made to apply the DMC method in the power industry. Rovnak and Corlis [4] discussed theoretical and practical aspects of the DMC and presented simulation results of a supercritical boiler–turbine system. In their paper, DMC was applied to a supercritical boiler with three outputs: electric power, steam pressure, and steam temperature. Sanchez et al. [15] presented an application of DMC to steam temperature control of fossil power plants, and showed that the single-input single-output (SISO) DMC performs better than PID control. Lee et al. [5] developed a neural network-based predictive control for 500 MW supercritical once-though boiler. They used an online neural network model to describe the plant dynamics and used particle swam optimization for online optimization control. Hua et al. [6] presented simulation results of DMC based on state feedback to control reheat steam temperature of a 600 MW boiler.

Chaibakhsh et al. [7] presented a feedforward and feedback fuzzy control system to regulate the superheated steam temperature of a 440 MW once-through boiler. Moon et al. [16]–[18] developed adaptive DMC for a drum-type boiler–turbine system using a third-order model as a test bed. More recently, Kwang et al. applied inverse dynamic control and neural network control for a type of once-through boiler, respectively [19], [20].

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In this paper, an application of the MIMO DMC for steam temperature control of a large-scale USC once-through boiler–turbine system is presented. To control the steam temperatures in this large-scale power plant, four output variables (i.e., the outlet temperatures of platen superheater, finish superheater, primary reheater, and finish reheater) are controlled using four input variables (i.e., two spray valves, bypass valve, and damper). The step-response matrix for the MIMO DMC is constructed using the four input and the four output variables. The MIMO DMC controller is implemented in a full-scope power plant simulator with satisfactory performance.

The paper is organized as follows. An overview of the USC once-through boiler–turbine system and a full-scope dynamic boiler simulation model (DBSM) are presented in Section 2. The concept of MIMO DMC and the procedure for constructing the step-response matrix are illustrated in Section 3. Section 4 presents the simulation results. Concluding remarks are given in Section 5.

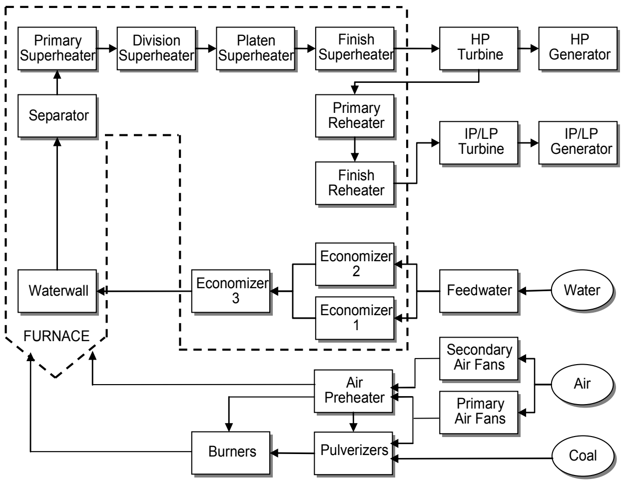

Fig. 1. Schematic of a large-scale USC boiler–turbine system

2. Boiler Model and Simulator

Fig. 1 shows the schematic of a large-scale USC once-through boiler–turbine system that is the subject of the present study. The subject system is reproduced using a full-scope DBSM. The system comprises four superhearters: (primary, division, platen, and finish), as well as two reheaters (i.e., primary and finish).

DBSM is capable of simulating realistic boiler behavior and displaying each numerical value in real time. In addition, the interface program of the DBSM, called *DBSM Editor*, maintains a real-time record of the numerical figures necessary for control and provides an interface to MATLAB. In turn, the controller programmed by MATLAB receives the simulation results from the DBSM for performing the DMC, and simultaneously sends the input values optimized to control the steam temperatures to the DBSM. Based on these input values, the DBSM again simulates the system. These processes are described in Fig. 2.

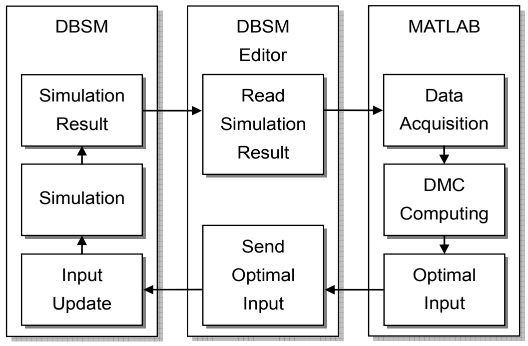

Fig. 2. Interface of the DBSM simulator with MATLAB controller

In Fig. 2, DBSM first simulates the USC boiler–turbine system. Then, DBSM editor reads the simulation results in real time and gives the simulation results to the controller programmed by MATLAB. After the simulation results are acquired, the DMC computes optimal input values to control the steam temperatures. Then, DBSM editor sends the computed optimal input values to the DBSM. The DBSM updates the input values and simulates the system again.

The structures of the superheater and reheater of the once-through boiler are described in Figs. 3 and 4, respectively. In Fig. 3, Spray2 and Spray3 inject atomized feedwater into the steam path, thereby reducing the steam temperatures of the platen superheater and finish superheater, respectively. In Fig. 4, a bypass is used to control the

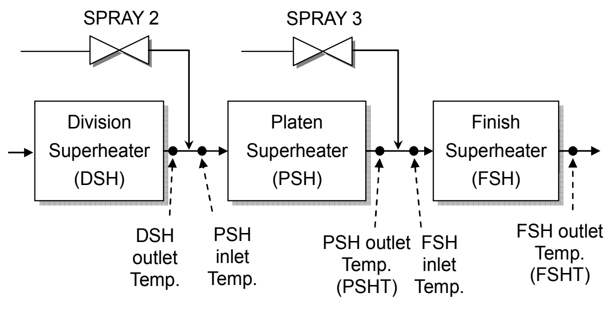

Fig. 3. Interface of the DBSM simulator with MATLAB controller

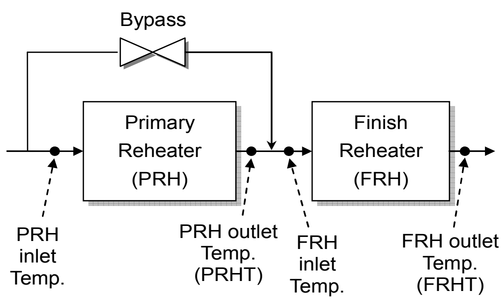

Fig. 4. Schematic of the reheater system

amount of steam flow to the primary reheater.

To control the steam temperatures in this study, four plant output or controlled variables are selected as the main variables: platen superheater outlet temperature (PSHT in Fig. 3), finish superheater outlet temperature (FSHT in Fig. 3), primary reheater outlet temperature (PRHT in Fig. 4), and finish reheater outlet temperature (FRHT in Fig. 4). In practice, although every temperature needs to be controlled, FSHT and FRHT need to be controlled more tightly.

Although several control variables (i.e., Spray1, Spray2, Spray3, Bypass, Damper, Emergency Spray, etc.) influence the output variables, Spray2, Spray3, Bypass, and Damper are chosen as input variables for simplicity. Although the Damper is not described in Figs. 3 and 4, the Damper controls the gas flow between the superheater and the reheater areas. The normalized operation range of these four input variables is from 0% to 100%.

3. MIMO DMC for Boiler–turbine System

3.1 MIMO DMC Algorithm

The design of the MIMO DMC follows the standard approach found in the process industry [21]. For a SISO system, the prediction equation in the MPC is in the following form:

$$Y_{k+1|k} = Y_{k+1|k-1} + S\Delta U_k + Y^d{}_{K+1|k} \tag{1}$$

where $Y_{k+1|k}$ is a $p\times 1$ vector representing a prediction of future output trajectory, $[y_{k+1|k},\ldots, y_{k+p|k}]^T$ at $t=k$, with p as the prediction horizon; $Y_{k+1|k-1}$ is a $p\times 1$ vector representing the unforced output trajectory $[y_{k+1|k-1},\ldots, y_{k+p|k-1}]^T$, which means an open-loop prediction while the input u remains constant at the previous value u_{k-1}; ΔU_k is an $m\times 1$ input adjustment vector $[\Delta u_k,\ldots,\Delta u_{k+m-1}]^T$ with m as the control horizon; and $Y^d{}_{k+1|k}$ is a $p\times 1$ vector representing an estimate of unmeasured disturbance on the future output. The matrix S is a $p\times m$ step-response matrix containing the step-response coefficients as follows:

$$S = \begin{bmatrix} s_1 & 0 & \cdots & 0 \\ s_2 & s_1 & \ddots & \vdots \\ s_3 & s_2 & \ddots & 0 \\ \vdots & \vdots & \ddots & s_1 \\ \vdots & \vdots & \cdots & \vdots \\ s_p & s_{p-1} & \cdots & s_{p-m+1} \end{bmatrix} \tag{2}$$

where s_i is the amplitude of step response at the ith sampling step.

To compute the inputs, the following online optimization is performed at every sampling time:

$$\min_{\Delta U_k} \left\| E_{k+1|k} \right\|_\Lambda + \left\| \Delta U_k \right\|_\Gamma \tag{3}$$

where $E_{k+1|k} = Y_{k+1|k} - R_{k+1|k} = [e_{k+1},\ldots, e_{k+p}]^T$ is a $p\times 1$ error vector, $R_{k+1|k} = [r_{k+1},\ldots, r_{k+p}]^T$ is a $p\times 1$ vector containing the desired or reference trajectory of the future output, and Λ and Γ are the weight matrices for the weighted Euclidean norm of the corresponding vectors. In addition, the following constraints are given:

$$Y_{\min} \le Y_{k+1|k} \le Y_{\max} \tag{4}$$

$$\Delta U_{\min} \le \Delta U_k \le \Delta U_{\max} \tag{5}$$

$$U_{\min} \le U_k \le U_{\max} \tag{6}$$

where U_k is an $m\times 1$ input vector, $[u_k,\ldots,u_{k+m-1}]^T$.

The resulting problem is a quadratic programming optimization problem with the inequality constraints (4)–(6). Once the optimal inputs $[\Delta u_k,\ldots,\Delta u_{k+m-1}]$ are computed, only the first input Δu_k is implemented and the rest is discarded as in a typical MPC control. The procedure is repeated at the next sampling time.

In this study, the boiler–turbine system is a MIMO system that has four inputs (i.e., Spray2, Spray3, Bypass, and Damper controls) and four outputs (i.e., PSHT, FSHT, PRHT, and FRHT). Therefore, the vectors $Y_{k+1|k}$, $Y_{k+1|k-1}$, $Y^d{}_{k+1|k}$, $R_{k+1|k}$, and $E_{k+1|k}$ are extended to $4p\times 1$ vectors and ΔU_k is a $4m\times 1$ vector in Eqs. (1)–(6). The prediction equation of the boiler–turbine system is then in the following form:

$$\overline{Y}_{k+1|k} = \overline{Y}_{k+1|k-1} + \overline{S}\Delta\overline{U}_k + \overline{Y}^d_{k+1|k} \tag{7}$$

where

$$\overline{Y}_{k+1|k} = [\overline{y}_{k+1|k} \quad \overline{y}_{k+2|k} \quad \cdots \quad \overline{y}_{k+p|k}]^T \tag{8}$$

$$\begin{aligned} &= [(y_{1(k+1|k)},\ y_{2(k+1|k)},\ y_{3(k+1|k)},\ y_{4(k+1|k)}) \ \cdots \\ &\quad (y_{1(k+p|k)},\ y_{2(k+p|k)},\ y_{3(k+p|k)},\ y_{4(k+p|k)})]^T \end{aligned} \tag{9}$$

$$\Delta\overline{U}_k = [\Delta\overline{u}_k \quad \Delta\overline{u}_{k+1} \quad \cdots \quad \Delta\overline{u}_{k+m-1}]^T \tag{10}$$

$$\begin{aligned} &= [(\Delta u_{1(k)},\ \Delta u_{2(k)},\ \Delta u_{3(k)},\ \Delta u_{4(k)}) \ \cdots \\ &\quad (\Delta u_{1(k+m-1)},\ \Delta u_{2(k+m-1)},\ \Delta u_{3(k+m-1)},\ \Delta u_{4(k+m-1)})]^T \end{aligned} \tag{11}$$

Subscripts 1, 2, 3, and 4 in Eqs. (9) and (11) are the indices for the four outputs and four inputs, and $\overline{S}$ is a $4p\times 4m$ step-response matrix containing 16-step responses as follows:

$$\overline{S} = \begin{bmatrix} \overline{s}_1 & \overline{0} & \cdots & \overline{0} \\ \overline{s}_2 & \overline{s}_1 & \ddots & \vdots \\ \vdots & \vdots & \ddots & \overline{s}_1 \\ \vdots & \vdots & \ddots & \vdots \\ \overline{s}_p & \overline{s}_{p-1} & \cdots & \overline{s}_{p-m+1} \end{bmatrix} \tag{12}$$

with

$$\overline{s}_i = \begin{pmatrix} s_i^{11} & s_i^{12} & s_i^{13} & s_i^{14} \\ s_i^{21} & s_i^{22} & s_i^{23} & s_i^{24} \\ s_i^{31} & s_i^{32} & s_i^{33} & s_i^{34} \\ s_i^{41} & s_i^{42} & s_i^{43} & s_i^{44} \end{pmatrix} \tag{13}$$

where every matrix element $\overline{s}_i$ is a 4×4 vector containing sixteen amplitudes of the step response at the ith sampling step, and s_i^{jk} is the step-response coefficient at the ith sampling step of the jth output resulting from the kth input.

The optimization problem (3) is also extended as follows:

$$\min_{\Delta\overline{U}_k} \left\|\overline{E}_{k+1|k}\right\|_{\Lambda} + \left\|\Delta\overline{U}_k\right\|_{\Gamma} \tag{14}$$

where $\overline{E}_{k+1|k} = \overline{Y}_{k+1|k} - \overline{R}_{k+1|k}$. Here, $\overline{R}_{k+1|k}$ is a $4p\times 1$ vector of desired trajectory for the four outputs, which are normally fixed with four constant set-point values.

3.2 Generation of Step-response Matrix

In the case when a reliable mathematical model is not available, the step-response matrix is obtained from experimental data. The usual process test signal is the step signal or a pseudo-random binary signal [22], [23]. In this paper, step-response matrix is developed by applying step inputs to the DBSM simulator.

When the electric power generation is stabilized with 825 MW, a 10% step is independently applied for each input variable. In other words, the input is increased 10% from steady-state value. Then, the corresponding responses are stored. Figs. 5-8 show the step responses of four output temperatures, where each response presents the temperature variation from the steady-state value.

Fig. 5 shows the response of Spray2. Spray reduces steam temperature by bringing superheated steam into direct contact with water; thus, the steam is cooled through the evaporation of the water. From the schematic of the superheater steam flow (Fig. 3), a step in Spray2 first decreases PSHT, then FSHT, and subsequently PRHT and FRHT. Similarly, in Fig. 6, a step in Spray3 decreases FSHT first, and then decreases PRHT and FRHT. In Fig. 6, PSHT shows a small decrease with noise than other responses. Since Spray3 is applied at the outlet of platen superheater in Fig. 3, the response of PSHT from Spray3 is ignored in this current study.

Fig. 7 shows the responses of Bypass. A step increase in Bypass increases the bypassed steam flow into the finish reheater and decreases the primary reheater steam flow. Therefore, the primary reheater heats less steam and PRHT is increased. However, FRHT is decreased because the primary reheater outlet steam is cooled by the bypassed steam into the finish reheater. Because the responses of PSHT and FSHT are small, they are ignored in this study.

Fig. 8 shows the responses of Damper. A step increase in Damper increases PRHT and FRHT while decreasing PSHT and FSHT because a step increase in Damper increases the gas flow to the reheater area.

Fig. 9 shows the system configuration. The DMC controller is applied to the DBSM, and the control algorithm optimizes the control performance (14) at every sampling step with the developed four-input four-output step-response model. The DBSM and MATLAB interface with the DBSM Editor, maintaining a real-time record of the numerical figures necessary for control. The controller programmed by MATLAB in turn receives the simulation results from the DBSM Editor while sending to the DBSM the input values.

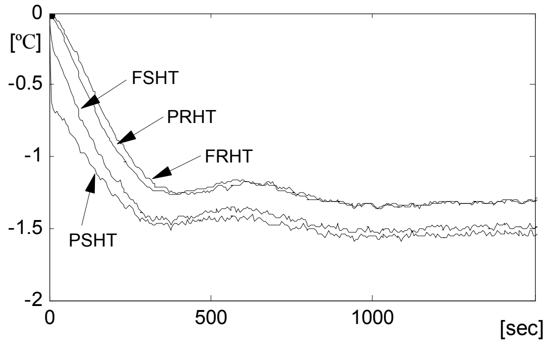

Fig. 5. Step responses of Spray2

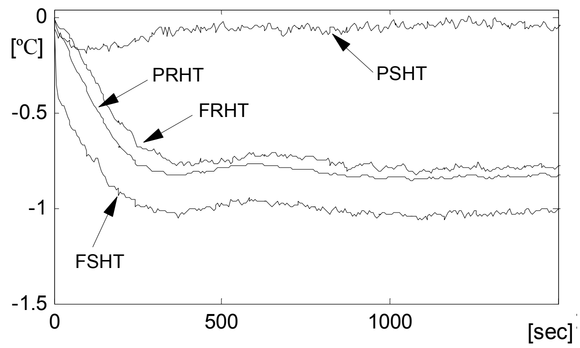

Fig. 6. Step responses of Spray3

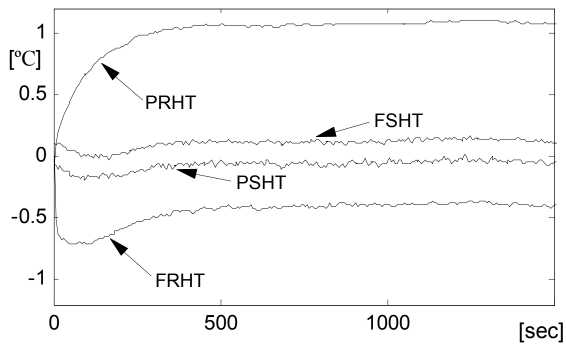

Fig. 7. Step responses of Bypass

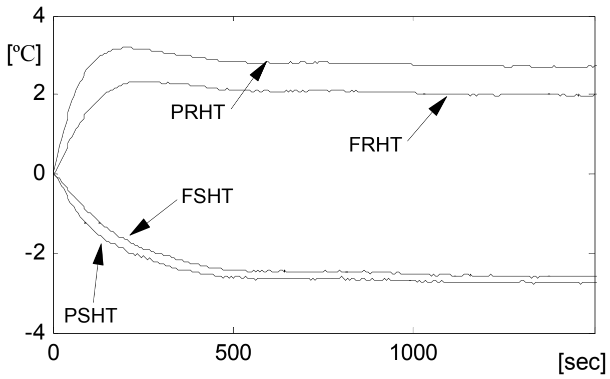

Fig. 8. Step responses of Damper

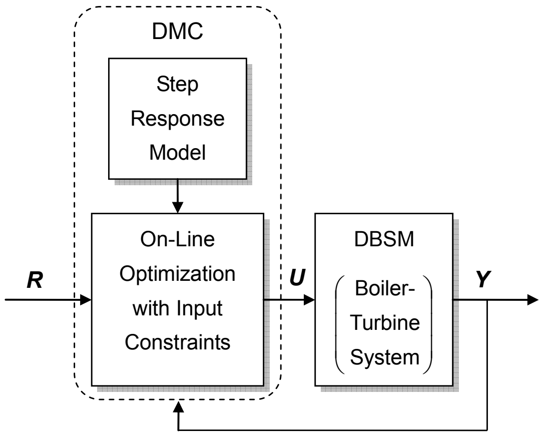

Fig. 9. DMC-based system configuration

4. Simulation Results

DBSM contains a conventional multiloop control algorithm with PIDs. For practical implementation, this conventional controller is carefully designed with many feedback loops and feedforward paths. Although the conventional multiloop PID control considers many output variables and manipulates many input variables (e.g., Spray1, Spray2, Spray3, Damper, Bypass, Emergency spray, and so on), only four output and input variables are considered in the MIMO DMC in this paper. The performance of the DMC is compared with that of the conventional multiloop PIDs.

Design of the DMC in this study is based on the MPC. First, the discrete time interval of DMC is set to 3 seconds, the prediction horizon to 1500 s, and the control horizon to 90 s. In the optimization function (14), the error and input change are weighted for the four outputs and four inputs:

$$\left\|\bar{e}_{k+1|k}\right\|_{\Lambda}=\begin{bmatrix} e_{1(k+1|k)} \\ e_{2(k+1|k)} \\ e_{3(k+1|k)} \\ e_{4(k+1|k)} \end{bmatrix}^T \begin{bmatrix} 100 & 0 & 0 & 0 \\ 0 & 300 & 0 & 0 \\ 0 & 0 & 90 & 0 \\ 0 & 0 & 0 & 50 \end{bmatrix} \begin{bmatrix} e_{1(k+1|k)} \\ e_{2(k+1|k)} \\ e_{3(k+1|k)} \\ e_{4(k+1|k)} \end{bmatrix} \quad (15)$$

$$\left\|\Delta\bar{u}_k\right\|_{\Gamma}=\begin{bmatrix} \Delta u_{1(k)} \\ \Delta u_{2(k)} \\ \Delta u_{3(k)} \\ \Delta u_{4(k)} \end{bmatrix}^T \begin{bmatrix} 75 & 0 & 0 & 0 \\ 0 & 25 & 0 & 0 \\ 0 & 0 & 2500 & 0 \\ 0 & 0 & 0 & 2500 \end{bmatrix} \begin{bmatrix} \Delta u_{1(k)} \\ \Delta u_{2(k)} \\ \Delta u_{3(k)} \\ \Delta u_{4(k)} \end{bmatrix} \quad (16)$$

where $e_{i(k+1|k)}$ indicates the error for the ith output values with i=1, 2, 3, and 4 for PSHT, FSHT, PRHT, and FRHT, respectively, and $\Delta u_{i(k)}$ indicates the change in the ith input with i=1, 2, 3, and 4 for Spray2, Spray3, Bypass, and Damper, respectively.

The control performance was evaluated by applying two step changes in electric power load demand as shown in Fig. 10, where the electric power demand is reduced to 775 MW from a nominal 875 MW in 400 seconds and increased form 775 to 975 MW in 500 seconds. For comparison purpose, the set points of four output variables are the same as in the multiloop PIDs in the DBSM: the set point for FSHT is 613 °C and that for FRHT is 624 °C at any power load demand. The set points of PSHT are 560.275 °C in the first step change and 559.151 °C in the second step change. In addition, the set points of PRHT are 538.235 °C in the first step change and 538.033 °C in the second step change.

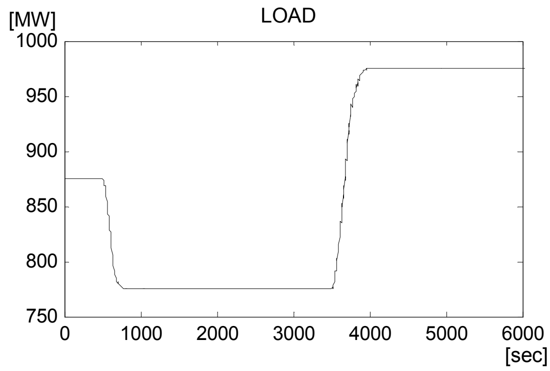

Fig. 10. Variation of electric power load demand

Figs. 11–14 show the comparisons of PID and the proposed DMC. Fig. 11 shows the PSHT responses of PID and DMC. In the first step change, DMC shows smaller overshoot and shorter settling time. The DMC also shows shorter settling time in the second step change. Fig. 12 shows the comparison of FSHT. Settling times of DMC control are shorter than those of PID controls in the two step changes. From the enlarged responses in the second step change, DMC shows smaller temperature variation from the set point.

Fig. 13 shows the responses of PRHT. In the two step changes, settling times of DMC are shorter than those of PID. Fig. 14 shows the responses of FRHT. Because the steam comes from a high-pressure turbine, more noise is observed than in other temperatures. Although it is not clearly represented in the figure, the maximum overshoot of PID is 8.77 °C, whereas that of DMC is 6.97 °C around 3680 s in the second step change.

The variations of corresponding inputs, Spray2 and Spray3 for superheater and Bypass and Damper for reheater, are shown in Figs. 15, 16, 17, and 18, respectively. Spray3 control is much smoother with DMC than with PID control.

For a quantitative comparison of PID and DMC, the sum of error squares in Figs. 11–14 is represented in Table 1. In the table, the percentage indicates the ratio of the error of DMC to that of the PID. The sums of error square of DMC with respect to PID are 59%, 57%, 69%, and 82% for PSHT, FSHT, PRHT, and FRHT, respectively. These results show better performance of the proposed DMC compared with that of PID control.

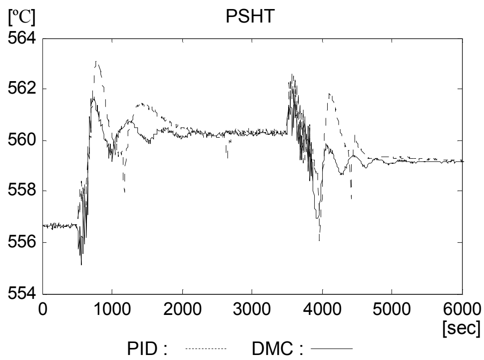

Fig. 11. Comparison of PSHT between PID and DMC

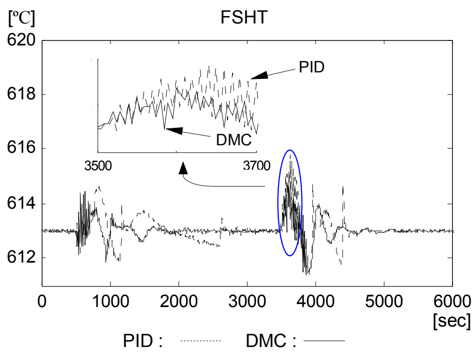

Fig. 12. Comparison of FSHT between PID and DMC

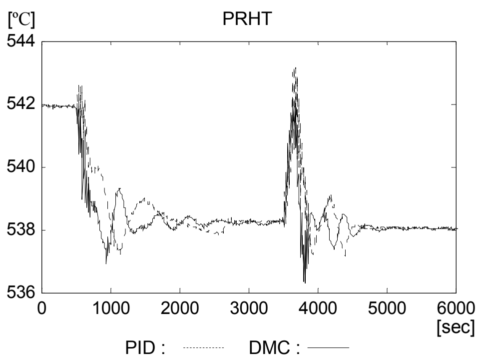

Fig. 13. Comparison of PRHT between PID and DMC

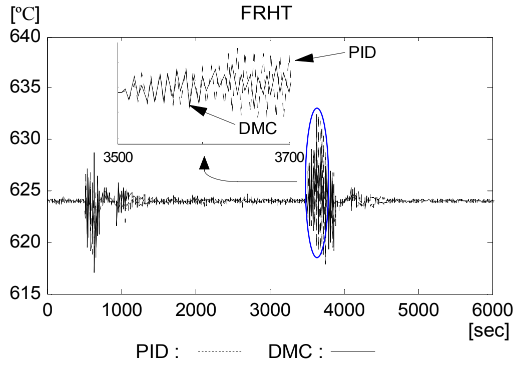

Fig. 14. Comparison of FRHT between PID and DMC

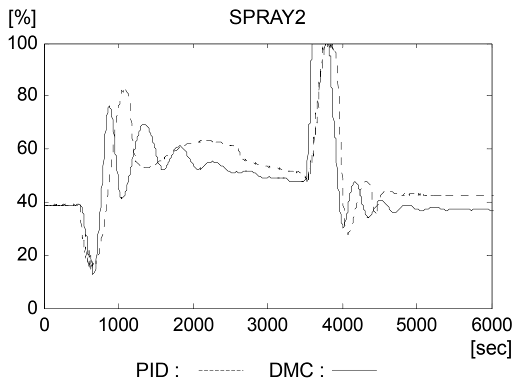

Fig. 15. Variation of Spray2

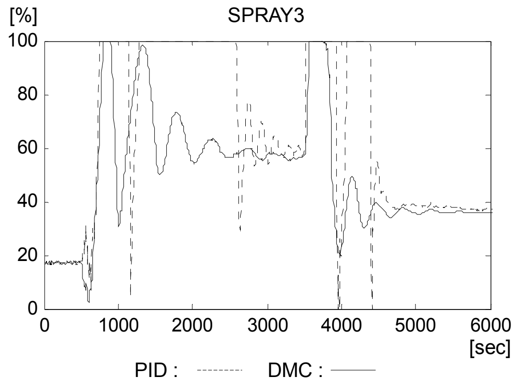

Fig. 16. Variation of Spray3

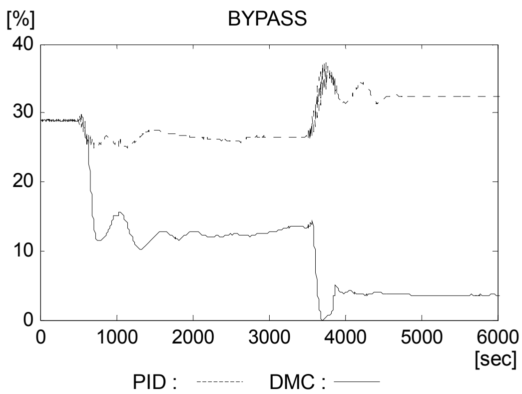

Fig. 17. Variation of Bypass

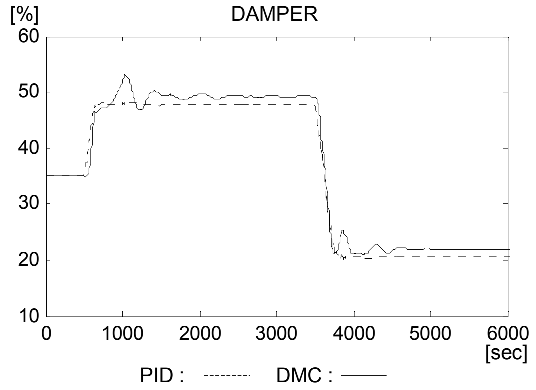

Fig. 18. Variation of Damper

Table 1. Comparison of the sum of error square

Output	PID	DMC
PSHT	3378.3	1995.2 (59%)
FSHT	1710.3	982.5 (57%)
PRHT	2703.3	1866.0 (69%)
FRHT	2761.9	2277.0 (82%)

5. Conclusion

MIMO DMC is developed for steam temperature control of a large-scale USC once-through boiler–turbine system. The USC response is represented by a step-response matrix for four-input and four-output system, where Spray2, Spray3, Bypass, and Damper controls are the four inputs and the outlet temperatures of platen superheater, finish superheater, primary reheater, and finish reheater are the four outputs. Online optimization is performed in the DMC using the step-response matrix to determine the MPC. The proposed DMC controller is implemented in a large-scale DBSM and compared to the multiloop PID control embedded in the simulator. Simulation results show better performance of the proposed DMC technique as compared with that of the PID control.

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