J Electr Eng Technol.2018; 13(1): 097-104
http://doi.org/10.5370/JEET.2018.13.1.097

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Supplementary Control of Conventional Coordinated Control for 1000 MW Ultra-supercritical Thermal Power Plant using Dynamic Matrix Control

Youngjun Lee*, Euiyeon Yoo*, Taehyun Lee* and Un-Chul Moon†

Abstract – This paper proposes supplementary control of conventional coordinated control of a power plant which directly affects network frequency. The supplementary control with dynamic matrix control is applied for 1000 MW power plant with ultra-supercritical (USC) once-through boiler. The supplementary control signal is added to the boiler feedforward signal in the existing coordinated control logic. Therefore, it is a very practical structure that can maintain the existing multi-loop control system. This supplementary controller uses the step response model for the power plant system, and on-line optimization is performed at every sampling step. The simulation results demonstrate the effectiveness of the proposed supplementary control in a wide operating range of a practical 1000 MW USC power plant simulator. These results can contribute the stable operation of power system frequency.

Keywords: Dynamic matrix control, Coordinated control, Boiler-turbine system, Ultra-supercritical boiler (USC) power plant

1. Introduction

For the participation of the steam power plants in regulating the network frequency, boilers and turbines should be co-ordinately controlled in addition to the base load productions. Lack of coordinated control over boiler-turbine may lead to power system oscillation [1-4]. Therefore, unlike usual boiler control problem, the output of power plant boiler control should include electric power, which means the dynamics of governor, turbine and generator are included to keep the network frequency in stable range.

The purpose of power plant control is to follow the load demand for the network frequency through droop control and automatic generation control (AGC). To track the load demand for the stable network frequency, the electric power output (MWO) and the main steam pressure (MSP) are simultaneously controlled by the boiler and turbine master controllers. This control structure is called as the boiler-turbine coordinated control [3, 4].

Ultra-supercritical (USC) boilers have been applied in the power plant industry since 2000. The steam used in an USC once-through boiler is maintained at a pressure of 250 bar and a temperature of about 600°C. This extreme condition results in high efficiency heat exchange cycle. Moreover, the USC boiler system is advantageous in terms of satisfying environmental regulations such as pollutant emissions [5, 6]. Owing to these benefits, the USC once-through boiler is being widely applied in large capacity thermal power plants all over the world.

The power plant with USC once-through boiler must be accompanied by a stable coordinated control system because many variables are strongly entangled and nonlinear. In the industrial sector, a multi-loop control based on proportional-integral-derivative (PID) is most widely used to control power plant systems. A PID controller has a simple structure and principle, it has been implemented widely. Therefore, it is easy for the field engineers to understand and use a PID controller [7].

For coordinated control of a power plant, many types of advanced control algorithms have been researched [8-11]. In [8], intelligent control has been developed for the supercritical boiler unit by using neural network inverse models. Liu and Chan developed neuro-fuzzy generalized predictive control (GPC) for the boiler system [9].

Model predictive control (MPC) has been widely used in the industrial process. MPC predicts future outputs based on the given process model, and calculates control inputs for these results. When compared to multi-loop control, MPC can better compensate for the errors caused by the differences between the plant and model. Moreover, MPC can handle multivariable interactions and inputs and output constraints. In [10], the most well-known MPC algorithm, i.e., dynamic matrix control (DMC), which uses a step response model (SRM) for the underlying boiler-turbine system, has been developed. In [11], a DMC using Fuzzy inference was developed for the simplified model of a boiler-turbine system. In [12], a nonlinear multivariable hierarchical MPC (HMPC) was developed for the USC

† Corresponding Author: School of Electrical and Electronics Engineering, Chung-Ang University, Korea. (ucmoon@cau.ac.kr).
* School of Electrical and Electronic Engineering, Chung-Ang University, Korea. (nowcas@daum.net)
Received: March 23, 2017; Accepted: August 28, 2017

power plant.

Nevertheless, it is still difficult to find examples where these advanced control algorithms have been practically applied to complex thermal power plants. One of the main reasons is that it is difficult for the field engineer to maintain advanced control systems. For example, in the emergency of a thermal power plant, a multi-loop control system can respond to emergencies by partial on–off of the multi-loop at the discretion of the field engineers. However, this type of solution is not feasible in the case of an advanced control system.

In this paper, the control performance is improved by applying a supplementary control to the existing boiler feedforward (BFF) signal of the multi-loop control in coordinated control system. It is very easy to implement this supplementary control structure in practice because it uses the existing multi-loop control logic. The supplementary controller can be easily stopped and removed without affecting the conventional control system. Therefore, the field engineers can quickly return to the familiar multi-loop control system.

The remainder of this paper is organized as follows: Section 2 introduces the full-scope of power plant model with the USC once-through boiler system. Section 3 presents the DMC algorithm and the development of the SRM. The simulation results are provided in Section 4. Finally, the conclusion is presented in Section 5.

2. A Power Plant Model and Coordinated Control

2.1 A Power Plant model with USC

Fig. 1 shows the dynamic simulation model (DBSM) of a 1000 MW power plant with USC once-through boiler-turbine system used in this study [1, 13]. DBSM is a field proven real-time simulator for the design and construction of a 1000 MW USC power plant developed by an industrial company. Each component of the DBSM shown in Fig. 1 is a differential equation based on the first principle equations such as mass balance, energy balance and momentum balance. The final output is electric power in Fig. 1. Though not presented in Fig. 1, the DBSM has an embedded coordinated control algorithm with numerous feedback loops and feedforward paths.

DBSM is capable of simulating realistic behavior of power plant and can display 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 data necessary for control and provides an interface with MATLAB.

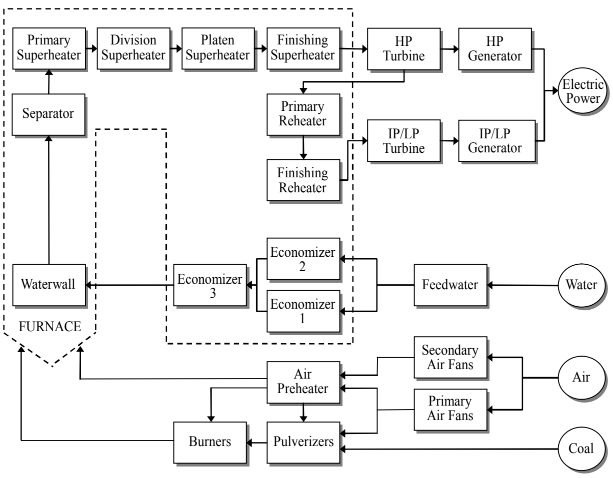

Fig. 1. Schematic of a 1000 MW large-scale power plant model with USC boiler-turbine system

2.2 Boiler control system in coordinated control

The purpose of power plant control is to follow the load demand through droop control and automatic generation control (AGC). To track the load demand for the stable network frequency, the electric power output (MWO) and the main steam pressure (MSP) are simultaneously controlled by the boiler and turbine master controllers. This control structure is called as the boiler-turbine coordinated control. Each of these controllers generates two signals: boiler master demand (BMD) and turbine master demand (TMD). The controllers of air, coal, and feedwater have BMD as an input signal, and the position of the governing valve to control the power output is determined by the TMD.

The structure of the existing boiler combustion system in

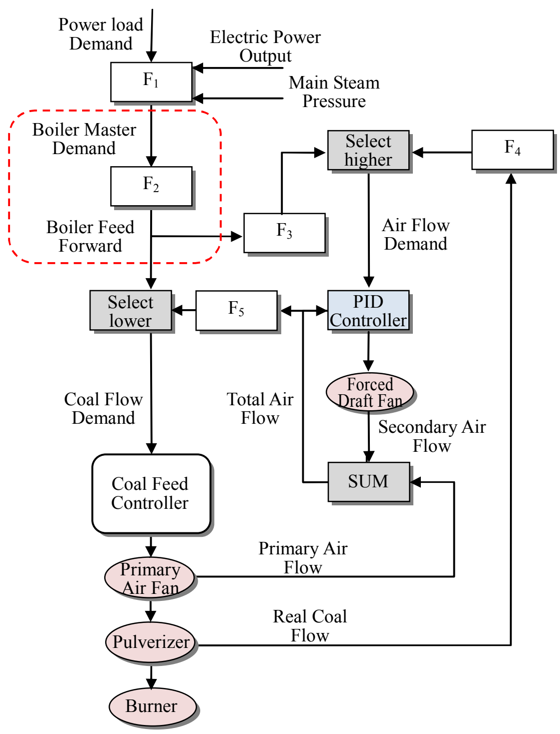

Fig. 2. Schematic of the conventional boiler combustion in coordinated control

DBSM is shown in Fig. 2 [14, 15]. Fundamentally, BMD is power load demand, and its unit is same as that of electric power. In the figure, BMD is the output from the F1 block and it is used as the feedforward signal for combustion control. This BMD is modified in the F1 block by considering the measured MWO and MSP. Because BMD is modified by MWO signals besides MSP, this control structure represents the coordinated control mode.

In Fig. 2, the blocks F2-F5 are static nonlinear functions used for unit conversion. F2 converts the BMD signal into the BFF signal whose unit is coal flow, T/H. The BFF signal is compared with the total air flow, and the smaller value is selected as the coal flow demand. Further, the unit of BFF is converted into air flow demand by F3. The BFF signal is also compared with the real coal flow, and the higher value is selected as the final air flow demand. The air flow demand then derives the PID controller for the forced draft fan of secondary air flow.

3. Simo Dmc for Boiler System

3.1 SIMO DMC structure

The supplementary control signal is added to the BFF signal of the existing multi-loop control logic in Fig. 2. Fig. 3 shows the proposed control structure using DMC. The red rectangle in Fig. 3 is same as the red rectangle in Fig. 2. In Fig. 3, the three outputs or control variables (CV) from the F1 block are MWO, MSP, and BMD, and the input or manipulated variable (MV) is the supplementary signal of BFF that is added to the BFF of the existing control system. These variables can be represented as follows:

$$\bar{y} = [y_1, y_2, y_3]^T = [MWO, MSP, BMD]^T \tag{1}$$

$$u = \Delta BFF \tag{2}$$

For an effective and tight control of a power plant, the basic outputs or CVs are MWO and MSP. In this paper, BMD is also added as a CV to prevent excessive change of the conventional BMD signal. The set points, MSP_{ref} and BMD_{ref} are determined to the steady-state values to track

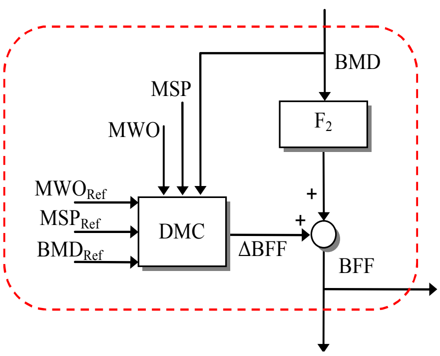

Fig. 3. Schematic of the proposed DMC

the power load demand. These values are determined by off-line testing of the existing multi-loop control of DBSM. The input or MV is ΔBFF, which is the supplementary control signal of BFF that is added to the BFF of the existing control system.

This supplementary DMC can be removed easily in case of an emergency without affecting the existing multi-loop control system. Therefore, the field engineers have the advantage of being able to quickly return to the familiar multi-loop control system.

3.2 DMC algorithm

This paper uses a DMC designed by the standard approach [16]. The plant for the supplementary DMC is a SIMO system that has one input and three outputs. The prediction equation of the boiler-turbine system is

$$\bar{Y}_{k+1|k} = \bar{Y}_{k+1|k-1} + \bar{S}\Delta U_k + \bar{Y}^d_{k+1|k} \tag{3}$$

where

$$\bar{Y}_{k+1|k} = [\bar{y}_{k+1|k}\ \ \bar{y}_{k+2|k}\ \cdots\ \bar{y}_{k+p|k}]^T \tag{4}$$

$$= [(y_{1(k+1|k)},\ y_{2(k+1|k)},\ y_{3(k+1|k)})\ \cdots$$
$$(y_{1(k+p|k)},\ y_{2(k+p|k)},\ y_{3(k+p|k)})]^T \tag{5}$$

$$\bar{Y}_{k+1|k-1} = [\bar{y}_{k+1|k-1}\ \ \bar{y}_{k+2|k-1}\ \cdots\ \bar{y}_{k+p|k-1}]^T \tag{6}$$

$$= [(y_{1(k+1|k-1)},\ y_{2(k+1|k-1)},\ y_{3(k+1|k-1)})\ \cdots \tag{7}$$
$$(y_{1(k+p|k-1)},\ y_{2(k+p|k-1)},\ y_{3(k+p|k-1)})]^T$$

$$\Delta U_k = [\Delta u_k\ \ \Delta u_{k+1}\ \cdots\ \Delta u_{k+m-1}]^T \tag{8}$$

$\bar{Y}_{k+1|k}$ is a $3p \times 1$ vector representing a prediction of the future output trajectory at time $t = k$, and p is the prediction horizon. $\bar{Y}_{k+1|k-1}$ is a $3p \times 1$ vector representing the unforced output trajectory, which means the 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 and m is the control horizon. $\bar{Y}^d_{k+1|k}$ is a $3p \times 1$ vector representing an estimate of unmeasured disturbance. In this paper, unmeasured disturbance is assumed as a constant which is the difference between measured output and predicted output. The subscripts 1, 2, and 3 in (5) and (7) are the indices for the three outputs.

$\bar{S}$ is a $3p \times m$ dynamic matrix containing two step responses as follows:

$$\bar{S} = \begin{bmatrix} \bar{s}_1 & \bar{0} & \cdots & \bar{0} \\ \bar{s}_2 & \bar{s}_1 & \ddots & \vdots \\ \vdots & \vdots & \ddots & \bar{s}_1 \\ \vdots & \vdots & \ddots & \vdots \\ \bar{s}_p & \bar{s}_{p-1} & \cdots & \bar{s}_{p-m+1} \end{bmatrix} \tag{9}$$

where

$$\overline{s}_i = \begin{pmatrix} s_i^{11} \\ s_i^{21} \\ s_i^{31} \end{pmatrix} \quad (10)$$

Every matrix element $\overline{s}_i$ is a 3×1 vector containing three amplitudes of the step response at i-th sampling step. s_i^{jk} is step response coefficient at the i-th sampling step of the j-th output obtained from the k-th input.

To compute the inputs, the following on-line quadratic optimization is performed at every sampling step:

$$\min_{\Delta U_k} \left\| \overline{E}_{k+1|k} \right\|_{\Lambda} + \left\| \Delta U_k \right\|_{\Gamma} \quad (11)$$

where

$$\begin{aligned} \overline{E}_{k+1|k} &= \overline{Y}_{k+1|k} - \overline{R}_{k+1|k} \\ &= [\overline{E}_{k+1|k} \ \ \overline{E}_{k+2|k} \ \cdots \ \overline{E}_{k+p|k}]^T \end{aligned} \quad (12)$$

$$\begin{aligned} = [(E_{1(k+1|k)},\ E_{2(k+1|k)},\ E_{3(k+1|k)}) \cdots \\ (E_{1(k+p|k)},\ E_{2(k+p|k)},\ E_{3(k+p|k)})]^T \end{aligned} \quad (13)$$

$$\overline{R}_{k+1|k} = [\overline{R}_{k+1|k} \ \ \overline{R}_{k+2|k} \ \cdots \ \overline{R}_{k+p|k}]^T \quad (14)$$

$$\begin{aligned} = [(R_{1(k+1|k)},\ R_{2(k+1|k)},\ R_{3(k+1|k)}) \cdots \\ (R_{1(k+p|k)},\ R_{2(k+p|k)},\ R_{3(k+p|k)})]^T \end{aligned} \quad (15)$$

$\overline{E}_{k+1|k}$ is a $3p \times 1$ error vector and $\overline{R}_{k+1|k}$ is a $3p \times 1$ vector of the desired trajectory for the three outputs, which are fixed with three constant set point values. Λ and Γ are the weights for the weighted Euclidean norm of the corresponding vectors. The following additional constraints are added to the abovementioned equations:

$$\Delta U_{\min} \le \Delta U_k \le \Delta U_{\max} \quad (16)$$

$$U_{\min} \le U_k \le U_{\max} \quad (17)$$

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 (QP) optimization problem with the inequality constraints (16)-(17). Once the optimal inputs $[\Delta u_k, \ldots, \Delta u_{k+m-1}]$ are computed, only the first input Δuk is implemented and the rest are discarded as in typical DMC control. The procedure is repeated at the next sampling step.

3.3 Generation of step-response matrix

In order to use the DMC algorithm, the SRMs of the three outputs with respect to input are developed. The usual process test signal is a step signal [17, 18]. In this paper, the step signal inputs are applied to the large-scale USC simulator to obtain SRMs.

When the electric power load is maintained at steady-state of 850 MW, 1.03 T/H of ΔBFF is additionally applied, which is 1% of the normal operation range. Further,

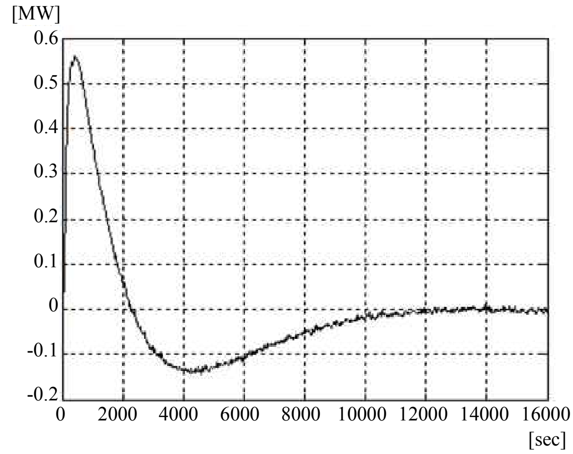

Fig. 4. Variation of electric output (MWO) due to step increase of ΔBFF

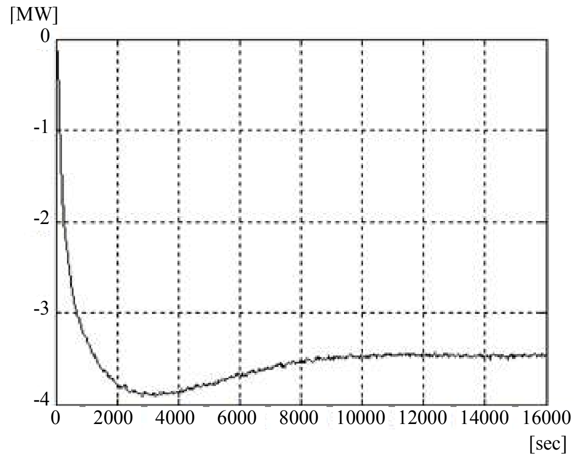

Fig. 5. Variation of boiler master demand (BMD) due to step increase of ΔBFF

corresponding output responses are stored. Figs. 4-6, and 7 show the step responses. In these figures, each response represents the normalized variation from its steady-state value.

Fig. 4 shows the step response of MWO for the step increase of ΔBFF at t = 0 s. Because the BFF is directly proportional to the quantity of coal and air, an additional step increase of the BFF increases the coal and air flows at the initial time. This increases the thermal energy and MSP. And, the MSP further increase the governor and turbine output. Then, finally the output of generator MWO is increased. Therefore, the dynamics of governor, turbine and generator are modeled in the step response in Fig. 4. However, it should be noted that the power load demand is fixed as 850 MW. The increased MWO and MSP are fed back to the F1 block in Fig. 2 as feedback signals. Then, F1 decreases BMD in order to maintain the MWO at 850 MW. This feedback action is repeated until MWO is set to 850 MW. Finally, Fig. 4 shows that MWO is stabilized to zero, which indicates a steady load of 850 MW.

Figs. 5 and 6 show the responses of BMD and BFF

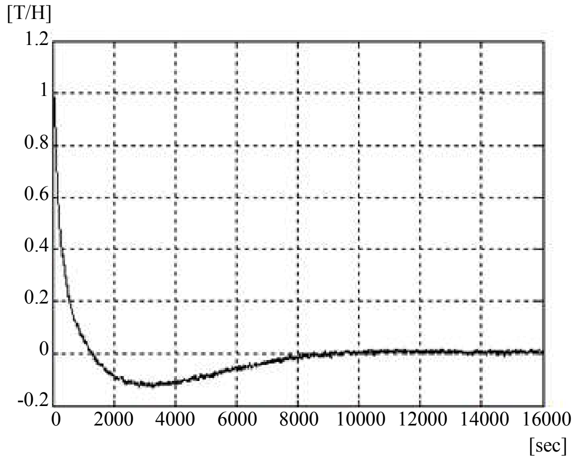

Fig. 6. Variation of boiler feed forward (BFF) due to step increase of ΔBFF

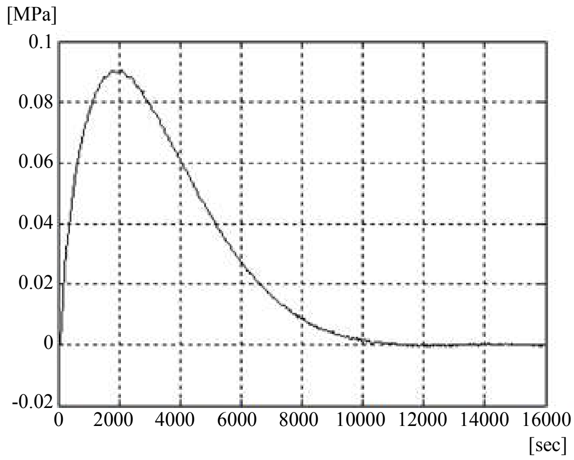

Fig. 7. Variation of main steam pressure (MSP) due to step increase of ΔBFF

respectively. At t = 0 s, the BMD is at 0 MW and BFF is at 1.03 T/H based on their steady-state values, as shown in Figs. 5 and 6. These figures illustrate that BMD decreases with time until BFF approaches zero so as to maintain MWO at 850 MW. Fig. 7 shows the response of MSP for the step increase of ΔBFF at t = 0 s. Though MSP initially increases as a result of increased BFF, the step response of MSP also finally converges back to zero as BFF returns to zero.

The responses of MWO, MSP, and BMD are formulated in (9), which is the SRM used in this paper. Further, they are used to minimize (11) at every sampling step by DMC.

4. Simulation Result

The tuning of the proposed supplementary DMC is based on the standard approach [10]. Theoretically, a small sampling time, and large prediction and control horizons are desirable. However, in practice, this increases the computational burden. In this study, the discrete time interval of DMC is set to 10 s, the prediction horizon is set to 1500 s, and the control horizon is set to 900 s.

Table 1. Steady-state values of CVs

MWO [MW]	MSP [MPa]	BMD [MW]
850	23.43	854.0
750	21.65	749.8
950	25.20	952.5

In (11), errors in the outputs are weighted and the input change is also weighted for the input as follows:

$$\overline{e}_{k+1|k} \begin{bmatrix} e_{1(k+1|k)} \\ e_{2(k+1|k)} \\ e_{3(k+1|k)} \end{bmatrix}^T \begin{bmatrix} 15 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & 0.1 \end{bmatrix} \begin{bmatrix} e_{1(k+1|k)} \\ e_{2(k+1|k)} \\ e_{3(k+1|k)} \end{bmatrix} \quad (18)$$

$$\Delta u_k = \left[\Delta u_k\right]^T \left[200\right]\left[\Delta u_k\right] \quad (19)$$

where $e_{i(k+1|k)}$ indicates the error in the i-th output value; $e_{1(k+1|k)}$ indicates the error in the MWO signal; $e_{2(k+1|k)}$ indicates the error in the MSP signal; and $e_{3(k+1|k)}$ indicates the error in the BMD signal. Further, Δu_k indicates ΔBFF at the k-step discrete time. Though the weight of BMD is relatively small, it plays a major role in suppressing the excessive changes in the BMD from the existing multi-loop control in coordinated control system.

The simulation considers two step changes in the electric power load variations. The electric load demand is first reduced to 750 MW from a nominal 850 MW after 500 s and then it is increased from 750 MW to 950 MW after 8500 s. Table 1 lists the steady-state values of the three CVs of the existing coordinated control structure.

Figs. 8-11 show the comparisons between the multi-loop control in coordinated control system and the proposed DMC. In these figures, the references are indicated by doted black lines; the responses of the multi-loop, by doted blue lines; and the responses of DMC, by solid red lines.

In Fig. 8, the MWO of both, the multi-loop and the DMC controls are presented. In the first step change, both responses look similar, and the response of DMC in the second step tracks the set point faster than the existing multi-loop control. Fig. 9 shows the two responses of the MSP. In the first step, though the response has a large undershoot, the response of the DMC tracks the set point considerably faster than existing multi-loop control. In the second step change, DMC shows very small settling time than that of the multi-loop control.

For a numerical comparison of the multi-loop control in conventional coordinated control and DMC, their performances as shown in Figs. 8 and 9 are represented in Tables 2 and 3, respectively. Tables 2 and 3 show the quantitative comparisons of Figs. 8 and 9 in terms of sum of error, rise time, and settling time. In every view point, the percentages in Tables 2 and 3 are less than 100%. This implies that the performance of the existing multi-

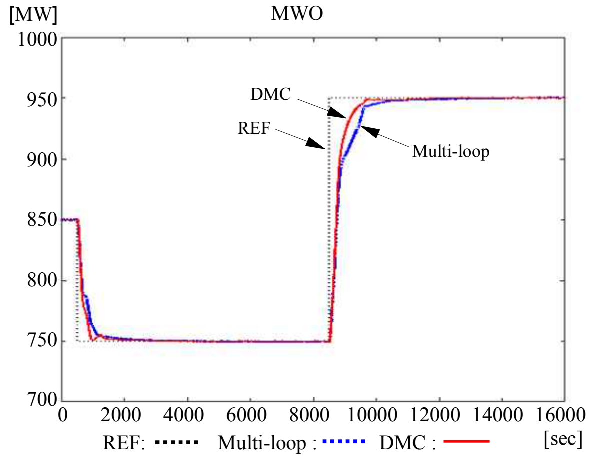

Fig. 8. Comparison of MWO between Multi-loop and DMC controls

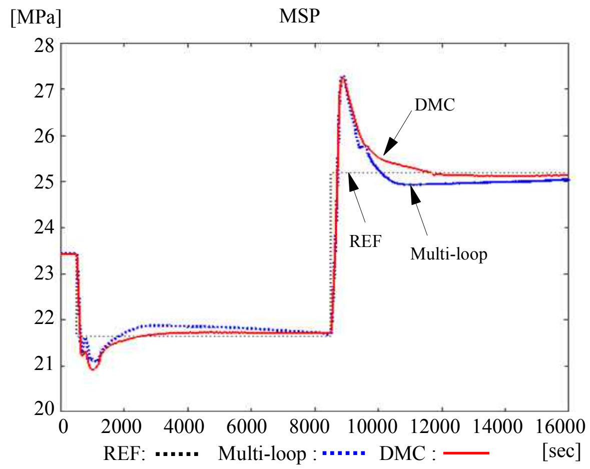

Fig. 9. Comparison of MSP between Multi-loop and DMC controls

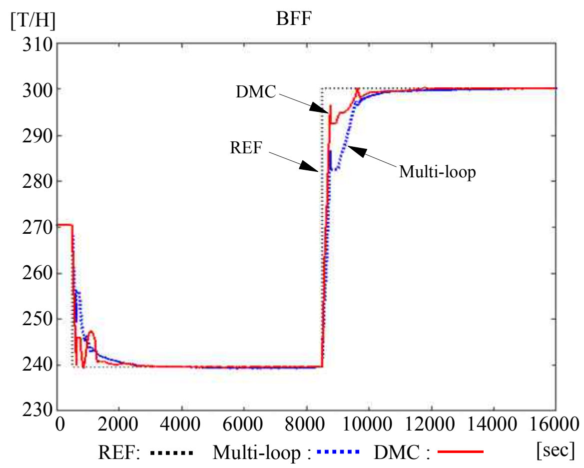

Fig. 10. Comparison of BFF between Multi-loop and DMC controls

loop control can be properly upgraded by the proposed supplementary control of DMC.

Table 2. Percentages of DMC/Multi-loop performance in MWO of Fig. 8

	First step change	Second step change
Sum of error	84.78 [%]	86.58 [%]
Rise time	65.77 [%]	59.80 [%]
Settling time	99.35 [%]	77.38 [%]

Table 3. Percentages of DMC/Multi-loop performance in MSP of Fig. 9

	First step change	Second step change
Sum of error	92.69 [%]	98.95 [%]
Rise time	98.80 [%]	99.38 [%]
Settling time	21.89 [%]	28.94 [%]

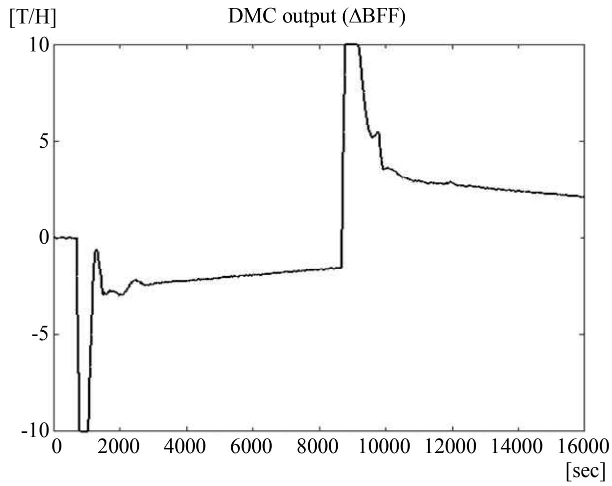

Fig. 11. Variation of DMC output (ΔBFF)

For a better understanding of the proposed supplementary control, the variations in BFF and ΔBFF as per the simulations are presented in Figs. 10 and 11, respectively. Fig. 10 shows the variations in BFF for both the control methods. A better performance of DMC is noted, which is due to the faster reaction of its BFF than that of the existing multi-loop control shown in Fig. 10. Fig. 11 explains the fast variation of DMC. Based on the real time calculation using the SRM, ΔBFF of DMC is negative in the first step change, and positive in the second step. This adjustment results in a fast reaction of the BFF as shown in Fig. 10.

5. Conclusion

The addition of a supplementary control signal to the existing coordinated control using DMC has been proposed in this paper for an effective control of the 1000 MW power plant with USC once-through boiler. The response of the USC power plant is represented by a step-response model for a one-input and three-output SIMO system, where ΔBFF is the input and MWO, MSP, and BMD are the three outputs. On-line optimization is performed in the

DMC algorithm using the SRM to determine the predictive control. The proposed DMC supplementary controller is implemented in a large-scale power plant simulator and is compared with the existing coordinated control embedded in the simulator. Simulation results show better performance of the proposed supplementary DMC technique in tracking the electric power output and pressure.

From a practical viewpoint, the proposed supplementary DMC can be easily applied in real power industries because the proposed structure maintains the existing coordinated control. Therefore, field engineers can cope with an emergency situation during a practical power plant operation. These results can contribute the stable operation of power system frequency.

Acknowledgements

This research was supported by the Chung-Ang University Graduate Research Scholarship in 2016 and by the Korea Institute for Advancement of Technology (KIAT) grant funded by the Korea Government - Ministry of Trade Industry and Energy(MOTIE) (No. N0001075) .

References

[1] J. Adams, D.R. Clark, J.R. Louis, and J.P. Spanbauer, "Mathematical Model of Once-Through Boiler Dynamics," *IEEE Trans. on Power Systems*, vol. 84, no. 2, pp. 146-156, 1965.

[2] R. T. Byerly et al., "Dynamic models for steam and hydro turbines in power system studies," *IEEE Committee Report, Trans. on PAS*, vol. 92, no. 6, pp. 1904-1915, Nov./Dec. 1973.

[3] F. P. de Mello et al., "Dynamic models for fossil fueled steam units in power system studies," *IEEE Trans. on Power Systems*, vol. 6, no. 2, pp. 753-761, May 1991.

[4] T. Inoue, H. Taniguchi and Y. Ikeguchi, "A model of fossil fueled plant with once-through boiler for power system frequency simulation studies," *IEEE Trans. on Power Systems*, vol. 15, no. 4, pp. 1322-1328, Nov. 2000.

[5] F. Alobaid, J. Storohle, B. Epple, and H.G. Kim, "Dynamic simulation of a supercritical once-through heat recovery steam generator during load changes and start-up procedures," *Applied Energy*, vol. 86, pp. 1274-1282, 2009.

[6] X. Liu, X. Tu, G. Hou, and J. Wang, "The Dynamic Neural Network Model of a Ultra Super-critical Steam Boiler Unit," *American Control Conference*, San Francisco, CA, USA, Jun 29-July 01, 2011.

[7] P. J. Gawthrop and P. E. Nomikos, "Automatic tuning of commercial PID controllers for single loop and multiloop applications," *IEEE Control Systems Magazine*, vol. 10, no. 1, pp. 34-42, 1990.

[8] L. Ma, K. Y. Lee and Z. Wang, "Intelligent coordinated controller design for a 600MW supercritical boiler unit based on expanded-structure neural network inverse models," *Control Engineering Practice*, vol. 53, pp. 194-201, 2016.

[9] X.-J. Liu and C. W. Chan, "Neuro-Fuzzy Generalized Predictive Control of Boiler Steam Temperature," *IEEE Trans. on Energy Conversion*, vol. 21, no. 4, pp. 900-908, 2006.

[10] U.-C. Moon and K. Y. Lee, "Step-Response Model Development for Dynamic Matrix Control of a Drum-Type Boiler-Turbine System," *IEEE Trans. on Energy Conversion*, vol. 24, no. 2, pp. 423-430, 2009.

[11] U.-C. Moon, and K. Y. Lee, "An Adaptive Dynamic Matrix Control with Fuzzy-Interpolated Step-Response Model for a Drum-Type Boiler-Turbine System," *IEEE Trans. on Energy Conversion*, vol. 26, no. 2, pp. 393-401, June 2011.

[12] X. Kong, X. Liu, and K. Y. Lee, "An Effective Nonlinear Multivariable HMPC for USC Power Plant Incorporating NFN-Based Modeling," *IEEE Trans. on Industrial Informatics*, vol. 12, no. 2, pp. 555-566, 2016.

[13] K. Y. Lee, et al., "Controller design for a large-scale ultrasupercritical once-through boiler power plant," *IEEE Trans. on Energy Conversion*, vol. 25, no. 4, pp. 1063-1070, Dec. 2010.

[14] D. Flynn, *Thermal power plant simulation and control*, IET Power and energy series 43, 2003.

[15] K. Lee et al., "Development of APESS software for power plant simulation," *ASME 2010 Pressure Vessels and Piping Conference*, vol. 9, Washington, USA, July 18-22, 2010.

[16] J. H. Lee, "Model Predictive Control in the Process Industries: Review, Current Status and Future Outlook," *Proceedings of the 2nd Asian Control Conference*, vol. II, pp. 435-438, Seoul. July 22-25, 1997.

[17] D. E. Seborg, T. E. Edgar, and D. A. Mellichamp, Process Dynamics and Control, John Willy & Suns, 1989.

[18] G. F. Franklin, J. D. Powell, and A. Emami-Naeini, Feedback Control of Dynamic System, Prentice-Hall, 2002.

Youngjun Lee received his B.S. degree in Electrical and Electronics Engineering from the Chung-Ang University, Seoul, Korea, in 2015. He is currently an M.S candidate in Electrical and Electronics Engineering at Chung-Ang University. His research interests include power system stability and control.

Euiyeon Yoo received his B.S. degree in Electrical and Electronics Engineering from the Chung-Ang University, Seoul, Korea, in 2017. He is currently an M.S candidate in Electrical and Electronics Engineering, Chung-Ang University. His research interests are in the area of power system analysis and automation.

Taehyun Lee received his B.S. degree in Electrical and Control Engineering from the Gyeonggi College of Science and Technology, Siheung, Korea, in 2016. He is currently an M.S candidate in Mechanical System Engineering, Chung-Ang University. His research interests include control and modeling of thermal power plant and emissions.

Un-Chul Moon received his B.S., M.S. and Ph.D. degrees from Seoul National University, Korea, in 1991, 1993 and 1996, respectively, all in Electrical Engineering. From 2000, he was with the Woo-Seok University, Korea, and from 2002 with the Chung-Ang University, Korea, where he is currently a Professor of Electrical Engineering. His current research interests are in the areas of power system analysis, computational intelligence and automation.