Proceedings of 2016 International Automatic Control Conference (CACS)
The Evergreen Laurel Hotel, Taichung, Taiwan, November 09-11, 2016

Design of Supervisory Cascade Model Predictive Control for Industrial Boilers

Pongsorn Keadtipod[1] and David Banjerdpongchai[2]
Department of Electrical Engineering, Faculty of Engineering Chulalongkorn University,
254 Phayathai Road, Phathumwan, Bangkok, 10330, Thailand
E-mail: [1]popolosu@hotmail.com, [2]bdavid@chula.ac.th

Abstract: This paper aims to improve the performance of boiler by applying cascade model predictive control to multiple control loops including water level, drum pressure and stream temperature. Since proportional–integral (PI) controllers do not provide satisfactory responses, model predictive control (MPC) is used to improve the performance of boiler in a framework of supervisory cascade control. We consider a linear time invariant (LTI) model of boiler system in which inputs are feedwater mass rate, fuel mass rate and attemperator spray mass rate, and outputs are water level, drum pressure and stream temperature. We present design of cascade control which PI controllers act as inner loop control and MPC acts as outer loop supervisory controller to improve performance of boiler. The design compares two control techniques, namely, standalone MPC and supervisory cascade MPC. We simulate step responses and compare performance in terms of maximum overshoot, settling time, and steady state error as well as bound of control inputs. Numerical results reveal that supervisory cascade MPC gives better performances than standalone MPC in all aspects.

Keywords: Model predictive control, Proportional–integral control, Supervisory cascade control, Industrial boiler

I. INTRODUCTION

Boiler is a critical component in power system because stream mass rate, stream temperature and stream pressure affect to performance of boiler. Although stream production setpoint is varied during operation, outputs of boiler which are water level, drum pressure and stream temperature must be controlled at desired level. Common controllers used in industry are PID control. It is simple structure and many tuning methods are available. However, PID control is rather limited to single-input single-output processes. For multivariable system, design of PID control is very complicated. Moreover, when considering input constraints, it is difficult to tune control parameters. On the other hand, MPC is one of advanced control strategies and has many advantages over conventional controllers. The advantages of MPC are summarized by [1].

- The concepts are intuitive and the tuning is relatively easy.
- It can be used to control a variety of processes.
- The multivariable case can easily be dealt with.
- It extension to the treatment of constraints.
- It is very useful when future references are known.

There are several algorithms of MPC. The main differences among themselves are the models used to represent process characteristics, noises, and cost function to be minimized. This type of control has been widely developed by researchers and control engineers as part of industrial automation control system technologies. There are many applications of MPC not only in the process industry such as industrial boiler [2, 3] but also control applications of cement industry [4], robot [5] and servos [6].

In our previous studies [2, 3], we show that MPC which give the better performance than PI control and more reasonable to apply MPC to real process. In design of MPC for industries, it is necessary to concern about how to implement MPC for performance improvement with minimum intervention of hardware. It is due to the fact that expert practitioners to configure, operate, monitor and maintain are limited [7]. Although there are many type of advanced controllers, users are still familiar with PID controllers. Therefore, supervisory cascade control is chosen in order to enhance the system performance by MPC while the operation of original system is preserved with existing PID controllers.

Supervisory cascade control is a control which consists of two controllers or more. The simplest supervisory cascade control system consists of two control loops (inner and outer). Cascade control is always used in a process which is slow dynamics process such as level, temperature, pressure and humidity. The advantages of supervisory cascade control are given as follows.

- Limit the effect of disturbance.
- Limit the effect of secondary process.
- Give more degree of freedom

From these advantages, cascade control can give faster process response and more robustness. However, supervisory cascade control should not be used in the process in which the dynamic of the inner loop are fast compared to those of the outer loop

This paper aims to design of supervisory cascade control which consists of MPC as outer loop control and PI control as inner loop control for improving the performance of boiler. We simulate the system responses and compare performance of process outputs measured by maximum overshoot, settling time, and steady state error as well as bound of control inputs.

The paper is organized as follows. In Section 2, we describe dynamic model of boiler. Section 3 elaborates on cascade control design, followed by numerical results in Section 4. Section 5 gives conclusions.

II. DYNAMIC MODEL OF BOILER

Consider schematic of boiler operation shown in Fig.1. [8]. The water tube boiler has multiple inputs, namely, feedwater mass rate, fuel mass rate and attemperator spray mass rate. Moreover, it has multiple outputs, namely, water level, drum pressure and stream temperature. Control inputs (manipulated variables) and process outputs (process variables) are defined in table 1.

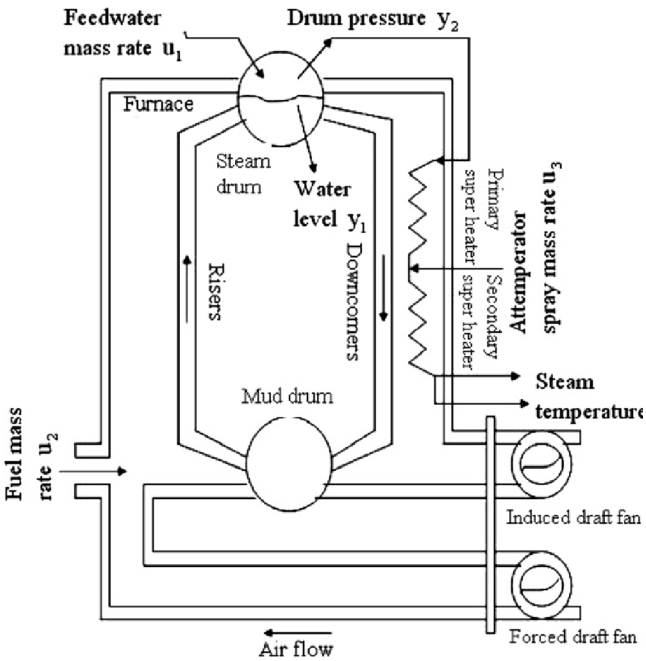

Fig.1 Schematic of boiler operation.

Table 1. Definition of control inputs and process outputs.

Control Inputs	
u_1	Feedwater mass rate (kg/s)
u_2	Fuel mass rate (kg/s)
u_3	Attemperator spray mass rate (kg/s)
Process Outputs	
y_1	Water level (m.)
y_2	Drum pressure (MPa.)
y_3	Stream temperature (°C)

Dynamic model of boiler is taken from [8]. Inputs and outputs from boiler are applied to system identification. A general form of linear time invariant multi-input multi-output (MIMO) open loop system is represent ed by the continuous time-domain state equation as follows.

$$\begin{aligned}\dot{x}_m &= A_m x_m + B_m u \\ y_m &= C_m x_m + D_m u\end{aligned} \tag{1}$$

where A_m, B_m, C_m and D_m are the state matrix, input matrix, output matrix and direct transmission matrix, x_m is the state vector, u is input and y is output and a transfer functions of boiler's system is represent as follows.

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \text{ where}$$

$$G_{11} = \frac{(-0.16s^2 + 0.052s + 0.0014)10^{-3}}{s^2 + 0.0268s + 0.000168}$$

$$G_{12} = \frac{(3.1s - 0.032)10^{-3}}{s^2 + 0.0415s + 0.00043}$$

$$G_{13} = 0$$

$$G_{21} = \frac{(-0.0395)10^{-3}}{s + 0.018}$$

$$G_{22} = \frac{(2.51)10^{-3}}{s + 0.0157}$$

$$G_{23} = \frac{(0.588s^2 + 0.2015s + 0.0009)10^{-3}}{s^2 + 0.0352s + 0.000142}$$

$$G_{31} = \frac{-0.000118s + 0.000139}{s^2 + 0.01852s + 0.000091}$$

$$G_{32} = \frac{0.448s + 0.0011}{s^2 + 0.0127s + 0.000095}$$

$$G_{33} = \frac{0.582s - 0.0243}{s^2 + 0.1076s + 0.00104}$$

III. SUPERVISORY CASCADE MPC DESIGN

Supervisory cascade control is a control which consists of two controllers or more. The simplest cascade control system consists of two control loops (inner and outer). We consider a structure of supervisory cascade control in Fig.2 which has MPC as primary controller and PI controller as secondary controller.

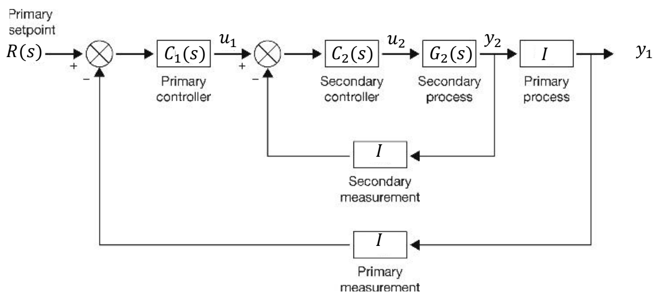

Fig. 2. Structure of supervisory cascade control.

In Fig. 2, controllers $C_1(s)$, $C_2(s)$ are MPC and PI controllers, respectively, whereas $G_2(s)$ is boiler's process. A general state space equation of PI controller is represented as

$$\begin{aligned}\dot{x}_c &= A_c x_c + B_c e \\ u &= C_c x_c + D_c e\end{aligned} \tag{2}$$

and transfer function of the PI controller is shown as follows.

$$C(s) = K_p + \frac{K_I}{s} \tag{3}$$

The inner control loop is used to form an augmented model in order to design supervisory MPC. From Eq. (1) and (2), the state space equation can be represented as

$$\begin{aligned}\dot{x}_p &= A_p x_p + B_p u \\ y_p &= C_p x_p + D_p u\end{aligned} \tag{4}$$

where $\dot{x}_p = \begin{bmatrix} \dot{x}_c \\ \dot{x}_m \end{bmatrix}$

$$A_p = \begin{bmatrix} A_c - B_c K D_m C_c & -B_c K C_m \\ B_m C_c - B_m D_c K D_m C_c & A_m - B_m D_c K C_m \end{bmatrix}$$
$$B_p = \begin{bmatrix} B_c - B_c K D_m D_c \\ B_m D_c - B_m D_c K D_m D_c \end{bmatrix}$$
$$C_p = [K D_m C_c \quad K C_m]$$
$$D_p = K D_m D_c,\ K = (I - D_m D_c)^{-1}$$

Principle of MPC is to find the control signal which provides the output response close to reference signal by solving the optimization problem. Cost function is shown in Eq. (5).

$$J = (R_s - Y)^T Q (R_s - Y) + \Delta U^T \bar{R} \Delta U \qquad (5)$$

where R_s is reference point, Y is output, Q is output weight, $\bar{R}$ is input rated weight and ΔU is rated input. Basic structure of MPC [1] is shown as Fig. 3.

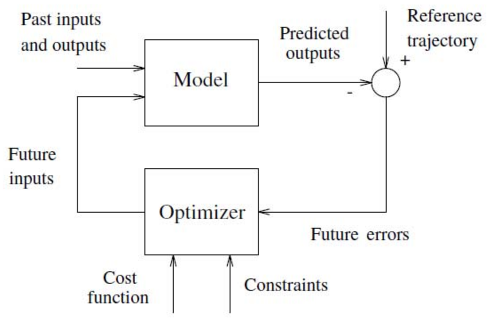

Fig. 3 Basic Structure of MPC [3].

In this paper, the optimization problem consists of cost function and constraints described as follows:

$$J = (R_s - Fx(k_i) - \emptyset\Delta U)^T Q (R_s - Fx(k_i) - \emptyset\Delta U) + \Delta U^T \bar{R} \Delta U$$

$$\begin{aligned} \text{subject to } & u_{1,min} \le u_1 \le u_{1,max} \\ & u_{2,min} \le u_2 \le u_{2,max} \\ & \vdots \\ & u_{n,min} \le u_n \le u_{n,max} \end{aligned}$$

In our design, we will fix Output weight (Q) and Control interval (T_c). There are 3 parameters which have to be selected: Input rated weight ($\bar{R}$), Prediction horizon (N_p), and Control horizon (N_c).

The boiler is specified at the operating point as follows.

$$y_0 = \begin{bmatrix} y_{10} \\ y_{20} \\ y_{30} \end{bmatrix} = \begin{bmatrix} 1 \\ 6.47 \\ 466.7 \end{bmatrix},\ u_{10} = \begin{bmatrix} u_{10} \\ u_{20} \\ u_{30} \end{bmatrix} = \begin{bmatrix} 40.68 \\ 2.102 \\ 0 \end{bmatrix}$$

Constraints of control inputs are based on physical limitation of operation:

$$0 \le u_1 \le 120,$$
$$0 \le u_2 \le 7,$$
$$0 \le u_3 \le 10.$$

To test the cascade control design, we consider an increase of 10% for water level, an increase of 5% for drum pressure and a decrease of 10% for stream temperature. We simulate responses using a modified model between the change of input and the change of output comparing to their original set points. Set points and constraints of control inputs are given as follows.

$$\Delta y = \begin{bmatrix} 0.1 \\ 0.33 \\ -46.7 \end{bmatrix},$$
$$-40.68 \le \Delta u_1 \le 79.32,$$
$$-2.102 \le \Delta u_2 \le 4.898,$$
$$0 \le \Delta u_3 \le 10.$$

IV. NUMERICAL RESULTS

PI control tuned by Zeigler-Nichols method is used as inner loop control. MPC with T_c=10, N_p=200, N_c= 50, Q=1 and $\bar{R}$=0.01 is used as outer loop control.

The comparison of output responses and control inputs between MPC and cascade control are displayed in Fig.4 and Fig.5. The performance measured by maximum overshoot and settling time, as well as bound of control inputs are compared and displayed in table 3 and table 4. The results show that supervisory cascade MPC gives faster responses than MPC. The steady state errors of both control techniques are zero. Moreover, control inputs of both cases satisfy the design constraints. In summary, the cascade control gives the better performance.

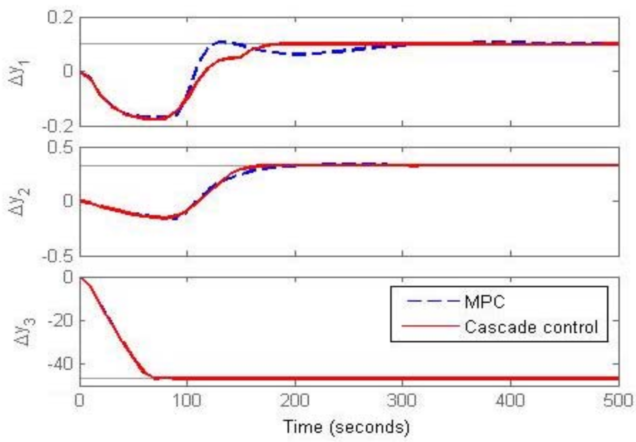

Fig.4. Comparison of output responses using MPC and cascade control.

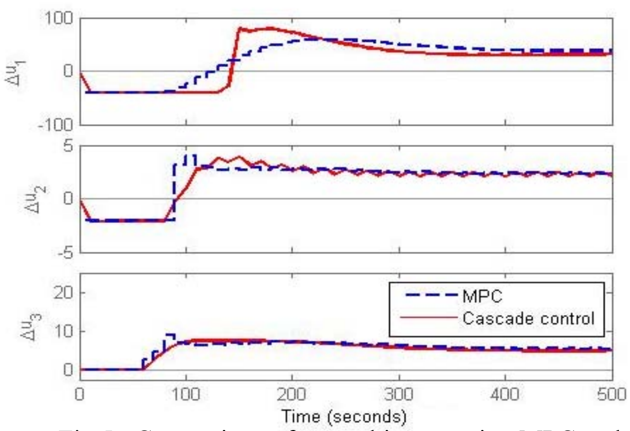

Fig.5. Comparison of control inputs using MPC and cascade control.

Table 3. Performance comparison between MPC and cascade control.

OUTPUT	Overshoot %		2% Settling time	
	MPC	Cascade control	MPC	Cascade control
Δy_1	7	1	314	184
Δy_2	1	0	204	177
Δy_3	0	0	68.1	56.7

Table 4. Bound of control inputs when applying MPC and cascade control.

INPUT	Constraint	MPC	Cascade Control
Δu_1	-40.68 to 79.32	-40.67 to 59.30	-40.67 to 79.30
Δu_2	-2.102 to 4.898	-2.10 to 4.02	-2.10 to 3.93
Δu_3	0 to 10	0 to 8.99	0 to 7.58

V. CONCLUSIONS

For stream production of boiler, outputs of boiler must be controlled at desired levels and optimal control system is needed. This paper presents design of supervisory cascade MPC to improve the performance of boiler while maintain the control inputs within constraints. We simulate output responses and compare performance with that obtained by standalone MPC. The results show that supervisory cascade MPC gives superior output performance.

REFERENCES

[1] E.F. Camacho and C. Bordons, Model predictive control. Springer, 2007, 2nd ed,, pp.1-10.

[2] P. Keadtipod and D. Banjerdpongchai. Design of Linear Model Predictive Control for Industrial Boilers. In Proc. EECON 39, Petchburi, Thailand, Nov. 2016. (Under review)

[3] V. Vitali, P. Eduard, V. Kristina, T. Aleksei and B. Juri. Application of MPC to Industrial Water Boiler Control System in District Heat Plant. In Proc. of International Conference on Control, Automation, Robotics and Vision, Dec. 2014, pp 1609 - 1614.

[4] D.W. Clarke. Application of Generalized Predictive Control to Industrial Processes. IEEE Control Systems Magazine, 1988, vol. 8, no.2, pp.49–55.

[5] J. Gomez Ortega and E.F. Camacho. Mobile Robot Navigation in a Partially Structured Environment using Neural Predictive Control. Control Engineering Practice, vol. 4, no. 12, Dec. 1996, pp. 1669-1679.

[6] J. Richalet, A. Rault, J.L. Testud, and J. Papon. Model Predictive Heuristic Control: Application to Industrial Processes. Automatica, 1978. vol. 14, no.2, pp.413–428.

[7] M.G. Forbes, R.S. Patwardhan, H.Hamadah and R.B.Gopaluni. Model Predictive Control in Industry: Challenges and Opportunities. In Proc. The 9th IFAC Symposium on Advanced Control of Chemical Processes, Whistler, Canada, June 2015, vol. 48, no. 8, 2015, pp.531-538.

[8] H. Moradi and F. Bakhtiari-Nejad, Improving boiler unit performance using an optimum robust minimum-order observer. Energy Conversion and Management, 2011, vol. 52, no.3, pp.1728-1740.

[9] C. Sidney Burrus. Digital Signal Processing and Digital Filter Design. CONNEXIONS Rice University, Houston, Texas, 2012, pp.241-246.