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GPC-BASED PI PRESSURE CONTROL FOR A THERMAL POWER PLANT

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Abstract. *This paper presents a new pressure control system for the furnace of a thermal power plant boiler. Such a system has nonlinear dynamics, and so it cannot be sufficiently controlled using linear control theory. Moreover, it is necessary to compensate for interference among variables, because this is a multivariable system with dead time. The plant is assumed to be a multiloop system, and we use the self-tuning method to design a linear controller for each loop. These controllers use proportional-integral (PI) compensation, with the parameters based on generalized predictive control (GPC). The interference among variables is treated as a disturbance, and the controllers use both a feed-forward compensator and the future reference trajectory of the GPC. We present numerical examples to evaluate the efficacy of using the feed-forward compensator and the future reference trajectory.*

Keywords: Pressure control, Furnace, Thermal power plant, Boiler, PI control, Generalized predictive control, Future reference trajectory

1. **Introduction.** This study presents a new pressure control system for the furnace of a thermal power plant boiler (hereinafter, "plant") [1, 2, 3]. The plant is multivariable, nonlinear, and has dead time and interference among the variables, so linear control theory is not sufficient for controlling it. Advanced control methods, such as model predictive control, have been shown to be helpful for the management of thermal power plants [4, 5], and proportional-integral-derivative (PID) control has been widely used because it is intuitive and because it can be adjusted according to the experience of the operators [6]. Hence, in practice, engineers working on site prefer PID control and so advanced control methods are not generally adopted. However, advanced control methods are a potential improvement, and one such proposed pressure control system uses self-tuning proportional-integral (PI) control [7, 8, 9].

In conventional approaches, the pressure is controlled by self-tuning PI controllers, with the design parameters based on generalized predictive control (GPC) [11, 12]. The sensitivity to the reference input can be reduced by using the future reference trajectory of the GPC [13], but conventional methods do not take advantage of this. In addition, it is well known that the effects of interference among variables can be reduced by using a feed-forward compensator [7, 9]. Hence, we can reduce the sensitivity of the reference input to interference among variables by utilizing the future reference trajectory and a feed-forward compensator [10]. However, it is not clear how this can be accomplished. In this study, we perform simulations with and without using the future reference trajectory and the feed-forward compensator, and we analyze the results.

This paper is organized as follows. Section 2 presents a model of a controlled plant, and Section 3 presents the proposed control system. In Section 4, we present and analyze numerical simulations using our design strategy with the future reference trajectory and the feed-forward compensator. Concluding remarks are presented in Section 5.

2. **Plant Model.** Consider a thermal power plant boiler [9]. The plant consists of a furnace, a flow control valve (FCV), a pressure control valve (PCV), a flow controller (FC), a pressure controller (PC), a forced draft fan (FDF), and an induced draft fan (IDF). The fuel and combustion air are sent to the furnace and are burned, and the exhaust gas is discharged. The FDF ensures that the air enters the furnace at a specified pressure, and the IDF induces the exhaust gas to discharge via the chimney. The FCV and PCV are operated by the FC and PC, respectively, such that the inlet gas flow and the pressure in the furnace meet prescribed values.

The mathematical model of this controlled plant is as follows:

$$\frac{dH(t)}{dt} = F_1(t) - F_2(t), \quad VP(t) = \frac{RT}{M}H(t) \tag{1}$$

$$F_1(t) = C_{v1}(P_1 - P(t))(x_1(t) + 0.5), \quad F_2(t) = C_{v2}(P(t) - P_2)(x_2(t) + 0.5) \tag{2}$$

The notation used in Equations (1) and (2) is defined in Table 1.

Table 1. Notation used in the plant model

Symbol	Model parameter	Value
$H(t)$[kg]	gas hold up	
$F_1(t)$[kg/s]	inlet gas flow	$0 \leq F_1(t) \leq 2.5 \times 10^4$
$F_2(t)$[kg/s]	outlet gas flow	
$P(t)$[mmH$_2$O]	pressure in a furnace	$-10^2 \leq P(t) \leq 10^2$
V[m^3]	volume of a furnace	10^3
M[kg/kg-mol]	gas molecular weight in a furnace	28.97
R[J/kg-mol $\cdot$ K]	gas constant value	8314.41
T[K]	average temperature in a furnace	6.0×10^2
$C_{v1}[\frac{\text{kg}}{\text{s}}/\text{mmH}_2\text{O}]$	flow coefficient of FCV	1.1×10^2
$C_{v2}[\frac{\text{kg}}{\text{s}}/\text{mmH}_2\text{O}]$	flow coefficient of PCV	1.1×10^2
$X_1(s)$ $(= \mathcal{L}\{x_1(t)\})$	valve opening rate of FCV	
$X_2(s)$ $(= \mathcal{L}\{x_2(t)\})$	valve opening rate of PCV	
P_1	upstream pressure of FCV	180
P_2	downstream pressure of PCV	-220
Alp	flow unit conversion coefficient flow[Nm^3/h] $\rightarrow$ mass[kg/s] using Alp	0.000359

The models of the FCV and PCV are

$$\text{[FCV]} \qquad X_1(s) = \frac{e^{-L_1 s}}{T_1 s + 1}U_1(s) \tag{3}$$

$$\text{[PCV]} \qquad X_2(s) = \frac{e^{-L_2 s}}{T_2 s + 1}U_2(s) \tag{4}$$

where L_i is the dead time, T_i is the time constant, and $U_i(s)$ is the control input.

3. Controller Design.

3.1. Linear plant model and controller.

In this approach, we consider interferences between variables and nonlinearity as disturbances, so the PI controllers are based on the following linear model:

$$A_i\left(z^{-1}\right) y_i[k] = B_i\left(z^{-1}\right) u_i[k-1] + \xi_i[k] \qquad (i = 1, 2) \tag{5}$$

where $A_i\left(z^{-1}\right)$ is a first-order monic polynomial, $B_i\left(z^{-1}\right)$ is an m_i-th-order polynomial, $y_1[k]$ and $y_2[k]$ are the sampled normalized values of $F_1(t)$ and $P(t)$, respectively, $u_1[k]$ and $u_2[k]$ are the control inputs to the FCV and PCV, respectively, $\xi_i[k]$ is a Gaussian white noise disturbance, and z^{-1} is the backward shift operator.

The PI controllers can be expressed in a digital velocity form, as follows:

$$\Delta u_1[k] = C_1(1) r_1[k] - C_1\left(z^{-1}\right) y_1[k] \tag{6}$$

$$\Delta u_2[k] = C_2\left(z^{-1}\right) y_2[k] - C_2(1) r_2[k] \tag{7}$$

$$C_i\left(z^{-1}\right) = K_{p,i}\left(\Delta + \frac{T_s}{T_{I,i}}\right) \tag{8}$$

where $\Delta = 1 - z^{-1}$, $r_i[k]$ is the reference input to be followed by $y_i[k]$, $C_1\left(z^{-1}\right)$ and $C_2\left(z^{-1}\right)$ are the PI compensators in the FC and PC, respectively, $K_{p,i}$ is the proportional gain, $T_{I,i}$ is the integral time, and T_s is the sampling time. Note that $K_{p,i}$ and $T_{I,i}$ are determined such that the GPC laws are approximated by the PI controllers.

3.2. **GPC.** The PI controllers are based on the GPC, so here we consider the relevant laws.

The cost functions of the GPC are as follows:

$$J_1[k] = E\left[\sum_{j=1}^{N_{y,1}} \{y_1[k+j] - w_1[k+j]\}^2 + \sum_{j=1}^{N_{u,1}} \lambda_1 \{\Delta u_1[k+j-1]\}^2\right] \tag{9}$$

$$J_2[k] = E\left[\sum_{j=1}^{N_{y,2}} \{w_2[k+j] - y_2[k+j]\}^2 + \sum_{j=1}^{N_{u,2}} \lambda_2 \{\Delta u_2[k+j-1]\}^2\right] \tag{10}$$

where $E[\cdot]$ is the expected value over $\xi_i[k]$, $N_{y,i}$ and $N_{u,i}$ are the predictive and control horizon, respectively, and λ_i is a weighting factor for the difference in the control input. The future reference trajectories are defined as follows [11, 12]:

$$w_i[k] = y_i[k] \qquad (i = 1, 2) \tag{11}$$

$$w_i[k+j] = (1 - \alpha_i) r_i[k] + \alpha_i w_i[k+j-1] \tag{12}$$

where α_i $(0 \leq \alpha_i < 1)$ is a design parameter that determines the shape of the trajectory.

Because the future predictive output is included in the cost function of the GPC, the Diophantine Equations (13) and (14) can be solved, and we obtain the polynomials $F_{i,j}\left(z^{-1}\right)$, $R_{i,j}\left(z^{-1}\right)$ and $S_{i,j}\left(z^{-1}\right)$:

$$1 = E_{i,j}\left(z^{-1}\right) \Delta A_i\left(z^{-1}\right) + z^{-j} F_{i,j}\left(z^{-1}\right) \tag{13}$$

$$E_{i,j}\left(z^{-1}\right) B_i\left(z^{-1}\right) = R_{i,j}\left(z^{-1}\right) + z^{-j} S_{i,j}\left(z^{-1}\right) \tag{14}$$

$$R_{i,j}\left(z^{-1}\right) = r_{i,0} + r_{i,1} z^{-1} + \cdots + r_{i,j-1} z^{-(j-1)} \tag{15}$$

Using the receding horizon, we obtain the following GPC laws:

$$G_{p,1}\left(z^{-1}\right) \Delta u_1[k] = P_1\left(z^{-1}\right) w_1[k + N_{y,1}] - F_{p,1}\left(z^{-1}\right) y_1[k] \tag{16}$$

$$G_{p,2}\left(z^{-1}\right) \Delta u_2[k] = F_{p,2}\left(z^{-1}\right) y_2[k] - P_2\left(z^{-1}\right) w_2[k + N_{y,2}] \tag{17}$$

where the coefficient polynomials are as follows:

$$\begin{aligned}
&P_i\left(z^{-1}\right) = p_{i,N_{y,i}} + p_{i,N_{y,i}-1} z^{-1} + \cdots + p_{i,1} z^{-(N_{y,i}-1)} \\
&F_{p,i}\left(z^{-1}\right) = p_{i,1} F_{i,1}\left(z^{-1}\right) + \cdots + p_{i,N_{y,i}} F_{i,N_{y,i}}\left(z^{-1}\right) \\
&S_{p,i}\left(z^{-1}\right) = p_{i,1} S_{i,1}\left(z^{-1}\right) + \cdots + p_{i,N_{y,i}} S_{i,N_{y,i}}\left(z^{-1}\right) \\
&G_{p,i}\left(z^{-1}\right) = 1 + z^{-1} S_{p,i}\left(z^{-1}\right) \\
&\left[\begin{array}{cccc} p_{i,1} & p_{i,2} & \ldots & p_{i,N_{u,i}} \end{array}\right] = \left[\begin{array}{cccc} 1 & 0 & \ldots & 0 \end{array}\right] \left(\boldsymbol{R}_i^T \boldsymbol{R}_i + \lambda_i \boldsymbol{I}\right)^{-1} \boldsymbol{R}_i^T
\end{aligned}$$

$$\boldsymbol{R}_i = \begin{bmatrix} r_{i,0} & 0 & \cdots & 0 \\ r_{i,1} & r_{i,0} & \ddots & \vdots \\ \vdots & & \ddots & 0 \\ r_{i,N_{u,i}-1} & r_{i,N_{u,i}-2} & & r_{i,0} \\ \vdots & & \ddots & \vdots \\ r_{i,N_i-1} & r_{i,N_i-2} & \cdots & r_{i,N_i-N_{u,i}} \end{bmatrix}$$

3.3. **Design of controller parameters.** In this subsection, we design the PI compensators so that the derived GPC laws are attained by the PI controllers.

Comparison of the PI controllers and the GPC laws gives the following shared conditions:

$$\frac{z^{N_{y,1}} P_1\left(z^{-1}\right)}{G_{p,1}\left(z^{-1}\right)} \simeq C_1(1), \quad \frac{F_{p,1}\left(z^{-1}\right)}{G_{p,1}\left(z^{-1}\right)} \simeq C_1\left(z^{-1}\right) \tag{18}$$

$$\frac{z^{N_{y,2}} P_2\left(z^{-1}\right)}{G_{p,2}\left(z^{-1}\right)} \simeq C_2(1), \quad \frac{F_{p,2}\left(z^{-1}\right)}{G_{p,2}\left(z^{-1}\right)} \simeq C_2\left(z^{-1}\right) \tag{19}$$

Generally, these equations are not satisfied, since the GPC compensators have higher order than the PI controllers do. First, the future reference trajectories (11) and (12) are rearranged to $w_i[k+j] = \alpha_i^j y_i[k] + \left(1 - \alpha_i^j\right) r_i[k]$ $(i = 1, 2)$ [13]. Next, $G_{p,1}\left(z^{-1}\right)$ and $G_{p,2}\left(z^{-1}\right)$ are replaced by their steady-state gain, $\nu_i \left(\stackrel{\Delta}{=} G_{p,i}(1)\right)$ $(i = 1, 2)$. Using ν_i, the PI parameters are calculated by solving the following equations:

$$C_1\left(z^{-1}\right) = \frac{F_{p,1}\left(z^{-1}\right) - p_{y,1}}{\nu_1}, \quad C_2\left(z^{-1}\right) = \frac{F_{p,2}\left(z^{-1}\right) - p_{y,2}}{\nu_2} \tag{20}$$

where $p_{y,i} = \sum_{j=1}^{N_{y,i}} \left(1 - \alpha_i^j\right) p_{i,j}$.

Because the pressure P is affected by changes in the control input of the FC, $u_1[k]$ is feed-forwarded to $u_2[k]$ to reduce this. In this case, $u_2[k]$ is replaced with $u_2[k] + C_{ff}\left(z^{-1}\right) u_1[k]$, where $C_{ff}\left(z^{-1}\right)$ is the feed-forward gain.

An actual plant cannot be sufficiently approximated by a linear plant model, such as that given by Equations (1)-(4). Hence, we consider the interference among variables to be a disturbance, and the coefficients of the polynomials $A_i\left(z^{-1}\right)$ and $B_i\left(z^{-1}\right)$ are estimated using a recursive least-squares approximation. The PI parameters are then updated by using these estimated coefficients.

4. **Numerical Example.** In this section, we analyze the results of simulations in which we consider the effects of assigning different values to the design parameters (α_1, α_2, and $C_{ff}\left(z^{-1}\right)$). The initial values of the controlled plant were set as follows: $F_1(0) = 1.10 \times 10^4$[Nm^3/H], $P(0) = -20$[mmH$_2$O], and $H(0) = 404$[kg]. The parameters for the two valves were as follows: $T_1 = 2$, $L_1 = 5$, $T_2 = 10$, and $L_2 = 1$. The reference values were as follows: $r_1[k]$ was set to 1.1×10^4 $(0 \le k < 200)$ or 1.6×10^4 $(200 \le k \le 400)$, and $r_2[k]$ was set to -20 $(0 \le k < 50)$ or -50 $(50 \le k \le 400)$. The duration of each simulation was 400s, and the sampling time T_s was 1s. We assumed that the plant output was not disturbed by noise.

The PI controllers were modeled as linear plants, and the coefficients were obtained by a recursive least-squares method. At each sampling step, the PI controllers were updated using the current estimate of the parameters. The orders of the polynomials $B_1\left(z^{-1}\right)$ and $B_2\left(z^{-1}\right)$ were set to $m_1 = 9$ and $m_2 = 5$, respectively, and we assumed that the dead time of each valve was known. The initial values of the estimated coefficients were as follows: $\hat{a}_{1,1}[0] = \hat{a}_{2,1}[0] = -0.7$, $\hat{b}_{1,i}[0] = 0.1$ $(i = 5, \cdots, 9)$, and $\hat{b}_{2,j}[0] = 0.1$ $(j = 1, \cdots, 5)$. In the recursive least-squares method, the forgetting factors were $\lambda_{e,1} = \lambda_{e,2} = 0.99$, and the initial values of the covariance matrices were $\alpha_{e,1} = \alpha_{e,2} = 10I$. The design parameters of GPC were set as follows: $N_{y,1} = N_{y,2} = 10$, $N_{u,1} = N_{u,2} = 1$, and $\lambda_{e,1} = \lambda_{e,2} = 20$. The design parameters of the reference trajectories, α_i $(i = 1, 2)$, and the feed-forward compensator, $C_{ff}\left(z^{-1}\right)$, were set as shown in Table 2.

The simulation results (pressure and inlet gas flow) are shown in Figures 1-18. In Case 1, interference among variables was not reduced since neither a feed-forward compensator nor a reference trajectory was employed. Furthermore, changes in the reference values result in a large overshoot and undershoot. In Case 2, the interference is suppressed by use of the feed-forward compensator, but the pressure is disturbed when the inlet gas flow is changed. Cases 3, 4, and 5 confirm the effectiveness of using the future reference trajectory without the feed-forward compensator, while Cases 6, 7, and 8 confirm the effectiveness of including the feed-forward compensator. These results show that use of the feed-forward compensator reduces the sensitivity to changes in F_1 but not to changes in P. Case 9 shows that when using the feed-forward compensator, the interference among variables can be reduced by adjusting the value of α_i.

TABLE 2. Design parameters

Case	1	2	3	4	5	6	7	8	9
α_1	0	0	0.92	0	0.92	0.92	0	0.92	0
α_2	0	0	0	0.96	0.96	0	0.96	0.96	0.71
$C_{ff}\left(z^{-1}\right)$	0	2.0	0	0	0	2.0	2.0	2.0	2.0

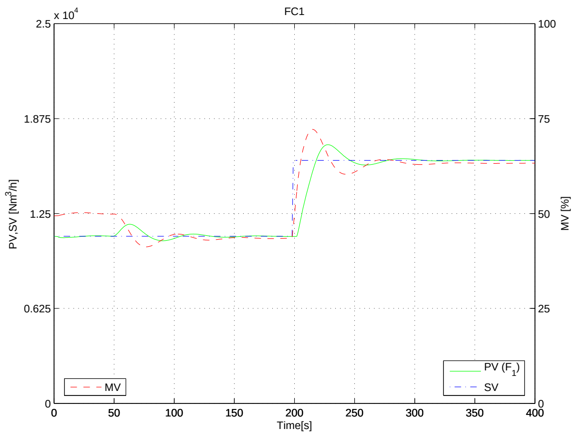

FIGURE 1. Case 1: Inlet gas flow

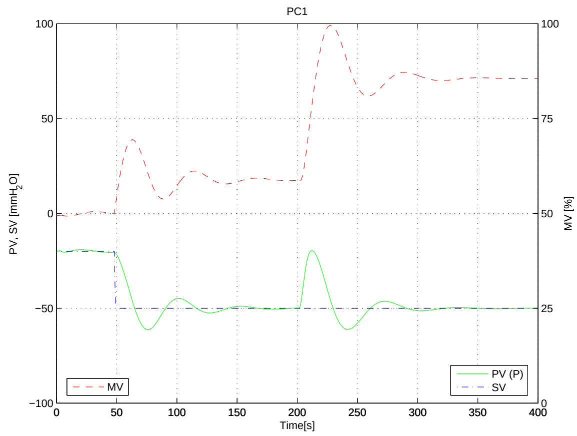

FIGURE 2. Case 1: Pressure

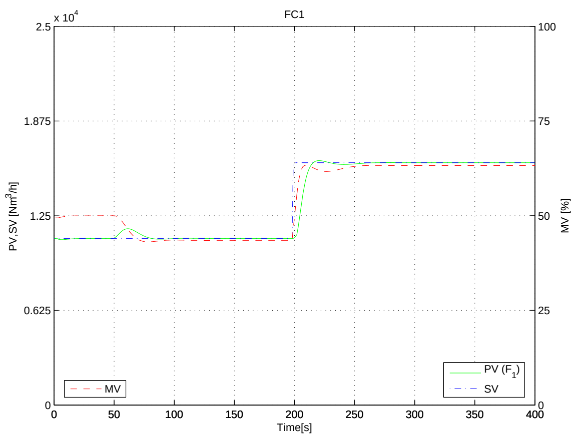

FIGURE 3. Case 2: Inlet gas flow

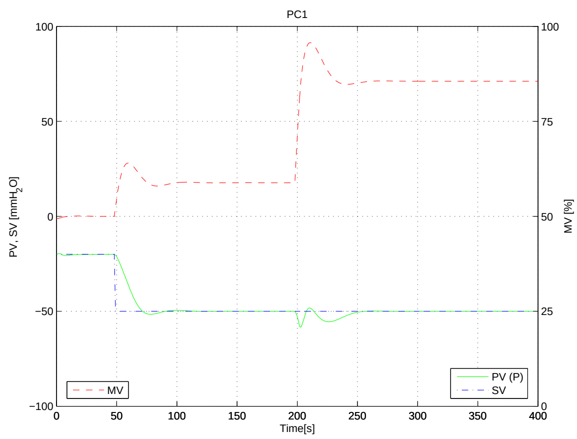

FIGURE 4. Case 2: Pressure

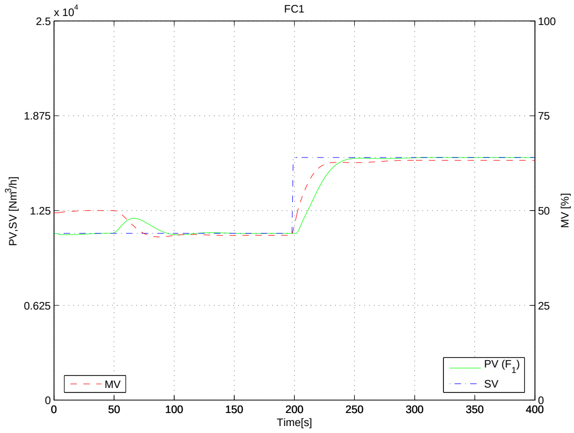

FIGURE 5. Case 3: Inlet gas flow

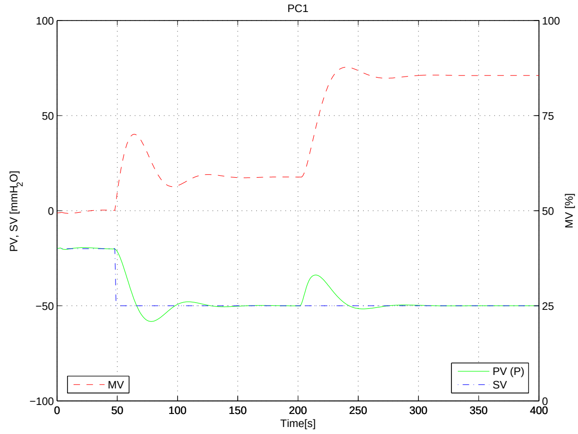

FIGURE 6. Case 3: Pressure

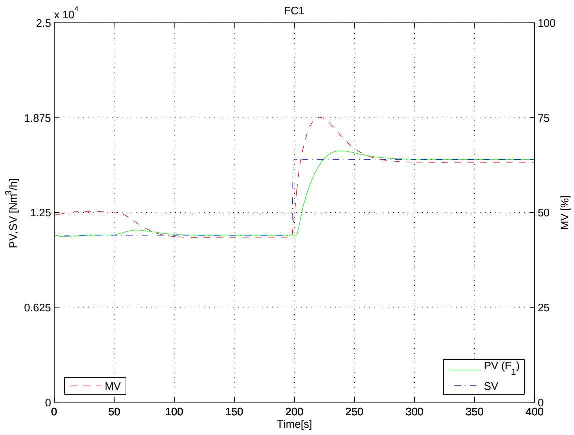

FIGURE 7. Case 4: Inlet gas flow

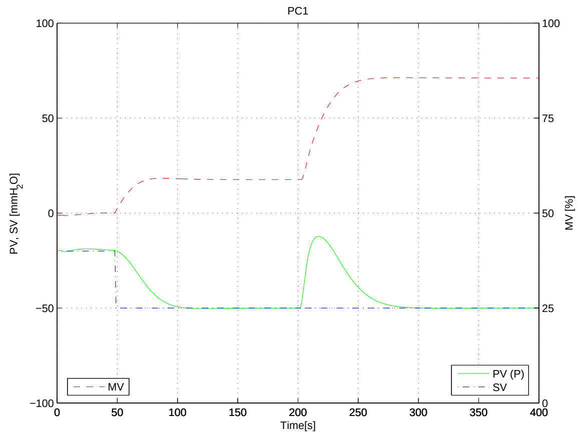

FIGURE 8. Case 4: Pressure

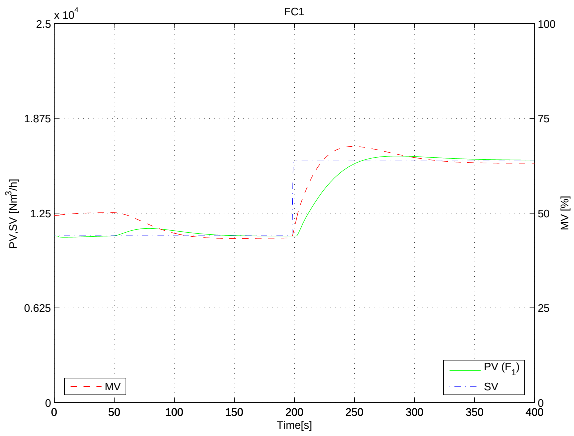

FIGURE 9. Case 5: Inlet gas flow

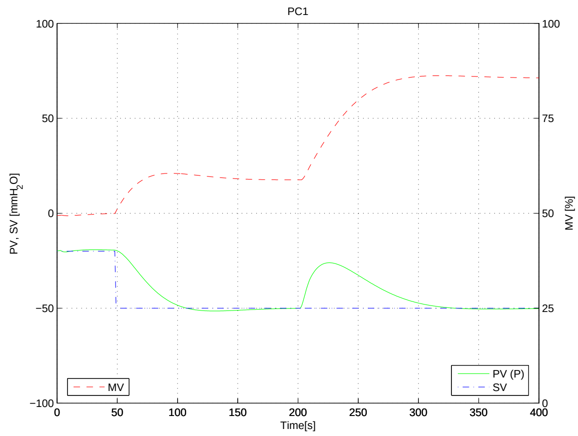

FIGURE 10. Case 5: Pressure

For $J_i = \sum |r_i[k] - y[k]|$ $(i = 1, 2)$, the control performances are shown in Table 3. Note that J_1 and J_2 can be effectively reduced by using $C_{ff}(z^{-1})$. When α_1 and $C_{ff}(z^{-1})$ are used, J_2 is reduced but J_1 increases; however, when α_2 and $C_{ff}(z^{-1})$ are used, J_1 is reduced but J_2 increases. When α_1 and α_2 are used without $C_{ff}(z^{-1})$, both J_1 and J_2 increase, because α_1 and α_2 are set to large values. However, when α_1, α_2, and $C_{ff}(z^{-1})$ are used, both J_1 and J_2 increase, but they can both be improved by adjusting α_1 and α_2.

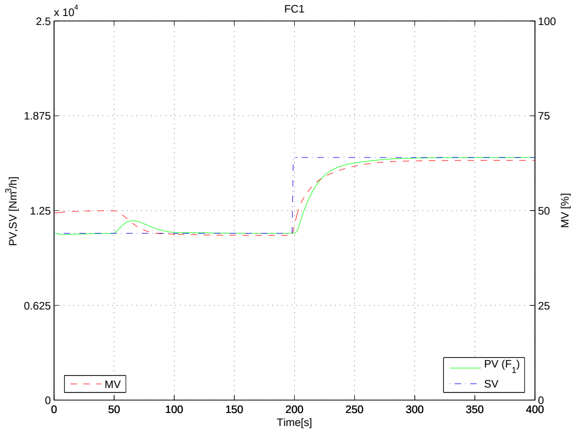

FIGURE 11. Case 6: Inlet gas flow

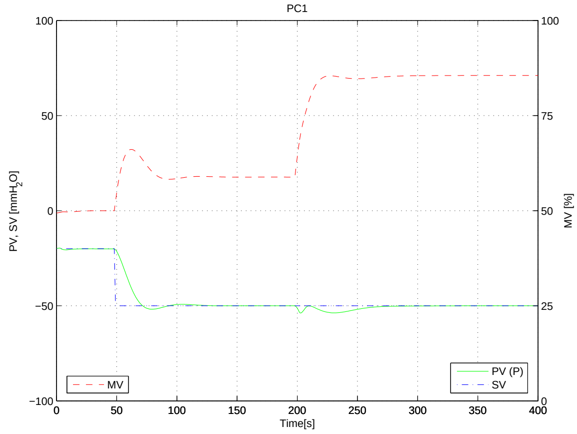

FIGURE 12. Case 6: Pressure

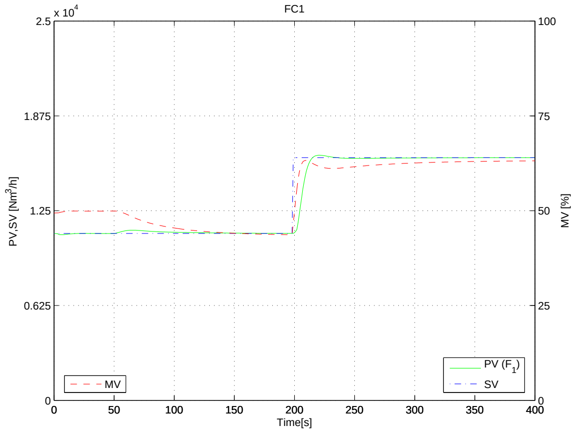

FIGURE 13. Case 7: Inlet gas flow

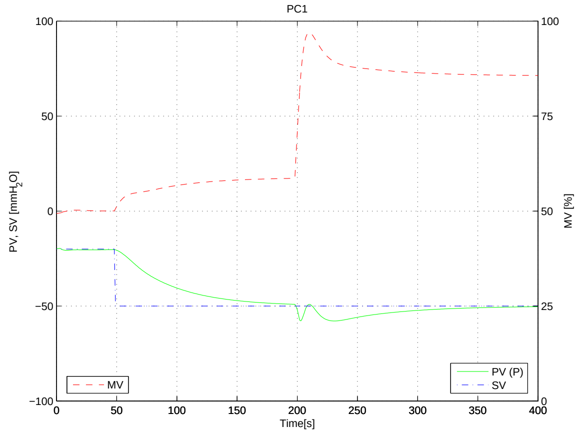

FIGURE 14. Case 7: Pressure

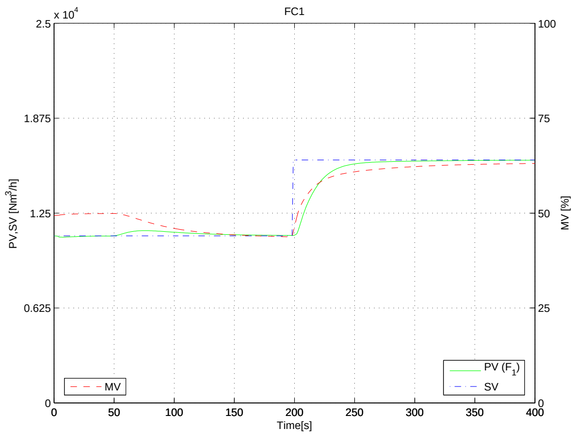

FIGURE 15. Case 8: Inlet gas flow

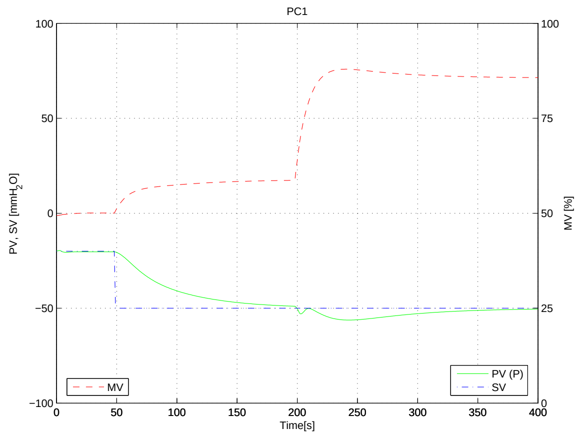

FIGURE 16. Case 8: Pressure

5. **Conclusion.** This paper has presented a design method for a pressure control system in the furnace of a thermal power plant boiler. This system uses PI controllers that are based on the GPC in order to compensate for the dead time. Because this system contains a multiple feedback loop, the interference among variables is suppressed by using a feed-forward compensator and the future reference trajectory of the GPC. The roles of the design parameters were investigated with numerical simulations. As an area of future work, we intend to evaluate the stability of this method in actual plants.

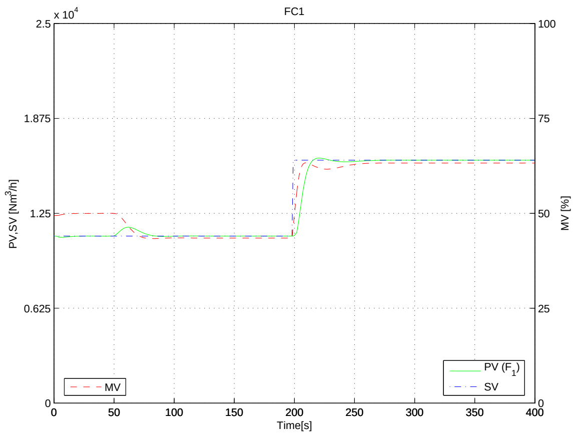

FIGURE 17. Case 9: Inlet gas flow

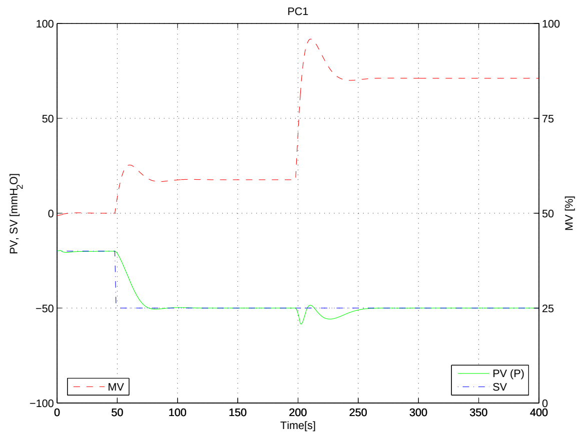

FIGURE 18. Case 9: Pressure

TABLE 3. Control performance

Case	1	2	3	4	5	6	7	8	9
J_1	4.41	2.48	5.51	3.87	6.71	5.38	2.45	5.26	2.45
J_2	7.37	2.80	4.68	10.7	11.6	2.75	9.65	9.50	2.99

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