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Independent Design of Multi-loop PI/PID Controllers for Multi-delay Processes

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Abstract**—** The interactions between input/output variables are a very common phenomenon encountered in the design of multi-loop controllers for interacting multivariable processes, which can be a serious obstacle for achieving a good overall performance of multi-loop control system. To overcome this impediment, the decomposed dynamic interaction analysis is proposed by decomposing the multi-loop control system into a set of n independent SISO systems with the corresponding effective open-loop transfer function (EOTF) within the dynamic interactions embedded explicitly. For each EOTF, the reduced model is independently formulated by using the proposed reduction design strategy, and then the paired multi-loop proportional-integral-derivative (PID) controller is derived quite simply and straightforwardly by using internal model control (IMC) theory. This design method can easily be implemented for various industrial processes because of its effectiveness. Several case studies are considered to demonstrate the superior of the proposed method.

Keywords**—**Multi-loop PID controller, internal model control (IMC), effective open-loop transfer function (EOTF)

I. INTRODUCTION

MULTI-LOOP (or decentralized) control has always been one of the most common control schemes for interacting multivariable plants in the process industries despite the availability of sophisticated full-scale multivariable control techniques that has developed in the literature of process control over a number of years (Rosenbrock [1], MacFarlane [2], Maciejowski [3], Camacho et al. [4], and Wang et al. [5]). The main reason for this popularity is due to its flexibility in operation, simplified design and simplified tuning. Generally, multi-loop control system is allowed to restructure during different operating conditions with purpose to handle changing control objectives, and the multi-loop controllers have much simpler structures and fewer tuning parameters than that of the centralized controllers. Thus, the product quality with lower cost can be naturally achieved by the manufacturers (Grosdidier and Morari [6]). However, the design of multi-loop control systems can be difficult because of the interactions among loops, which is a undesired phenomenon encountered in the closed-loop control systems as result of the existence of less diagonal dominance cases since the magnitude of off-diagonal elements in transfer function matrix increases along the range of frequency. To overcome this limitation, the tuning of a multi-loop PI/PID controller is usually used to minimize loop interactions.

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Our interest in this paper is to find a simple design method of the multi-loop PI/PID type controllers, which satisfies some important requirements as well motivated, analytically derived, loop failure tolerance ensured, and significant performance improvement. Based on the virtue of the independent design method and IMC-PID controller design formulas, the proposed method can compensate all deficiencies of previous design methods. The key idea is to decompose the multi-loop control system into each equivalent individual loops, and then the EIP model can be formulated based on the dynamic of each individual loop with the dynamic interactions embedded explicitly, and thus, the practicable controller is obtained independently in form of IMC-PID type controller without referring to the controller dynamics of other loops.

Several illustrated simulation examples are addressed to demonstrate the effectiveness of proposed method for various interacting multivariable processes.

II. PRELIMINARIES

Fig. 1 shows block diagrams of n x n general multi-loop system where loop i is open while all the other loops are closed. In Fig. 1, the notation is summarized as follows: $\mathbf{G}$ and g_{ii} are the transfer function matrix and its individual elements, respectively. $\bar{\mathbf{g}}^{ir}$ and $\bar{\mathbf{g}}^{ic}$ denote the ith row and column vector of matrix $\mathbf{G}$ where g_{ii} is discarded, respectively. $\bar{\mathbf{G}}^{i}$ denotes a matrix $\mathbf{G}$ where both the ith row and column are removed. The multi-loop controller and its individual elements are denoted by $\tilde{\mathbf{G}}_c$ and g_{ci}, while $\tilde{\mathbf{G}}_c^i$ denotes the diagonal matrix in which g_{ci} is dropped. Furthermore, r, u, and y are the set-point, manipulated, and controlled variable vectors, respectively while $\bar{\mathbf{r}}^i$, $\bar{\mathbf{u}}^i$, and $\bar{\mathbf{y}}^i$ are those without r_i, u_i, and y_i, respectively.

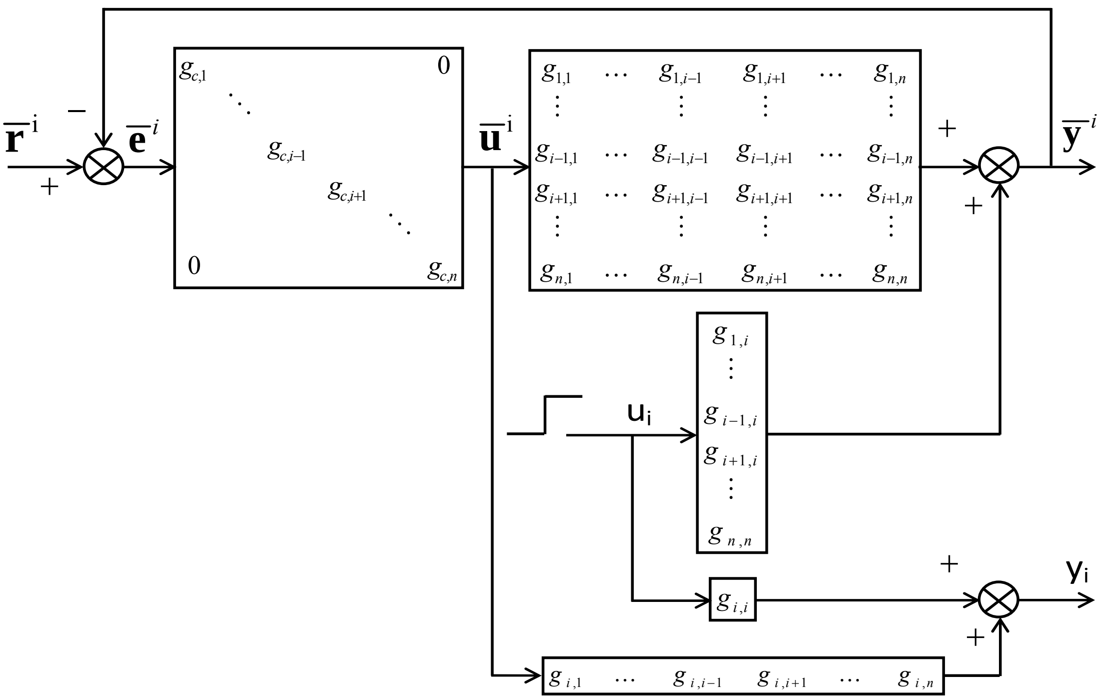

Fig. 1 Block diagram of $n\times n$ multi-loop system where all the other loops except loop i are closed.

III. Effective Open-loop Transfer Function and Dynamic Relative Gain

Consider a multi-loop system in Fig. 1 where loop i are open while all the other loops are closed. A multi-loop MIMO system can be considered as a set of n independent SISO systems with the corresponding EOTFs. Fig. 1 shows the block diagram for the concepts of the EOTF of loop i where loop i are open while all the other loops are closed. It is clear that tuning the controller of loop i in the multi-loop system should be done based on the EOTF rather than the original open-loop transfer function, $g_{i,i}$. The EOTF differs from the original open-loop transfer function, g_{ii}, by transmission interaction through a path including the other loops.

Consider the block diagram in Figure 1 with $\bar{\mathbf{r}}^i = 0$. Then $\bar{\mathbf{u}}^i$ is given by

$$\bar{\mathbf{u}}^i = -\tilde{\mathbf{G}}_c^i \bar{\mathbf{y}}^i = -\tilde{\mathbf{G}}_c^i (g_{ii} u_i + \bar{\mathbf{g}}^{ir} \bar{\mathbf{u}}^i) \tag{1}$$

Rearranging Eq. 1 yields

$$\bar{\mathbf{u}}^i = -\tilde{\mathbf{G}}_c^i \left(\mathbf{I} + \bar{\mathbf{G}}^i \tilde{\mathbf{G}}_c^i\right)^{-1} \bar{\mathbf{g}}^{ic} u_i \tag{2}$$

Therefore, the relation between y_i and u_i can be written as

$$\begin{aligned} y_i &= g_{ii} u_i + \bar{\mathbf{g}}^{ir} \bar{\mathbf{u}}^i \\ &= \left[g_{ii} - \bar{\mathbf{g}}^{ir} \tilde{\mathbf{G}}_c^i \left(\mathbf{I} + \bar{\mathbf{G}}^i \tilde{\mathbf{G}}_c^i\right)^{-1} \bar{\mathbf{g}}^{ic} \right] u_i \end{aligned} \tag{3}$$

The complication of dynamic interaction is clear from Eq. 3. The open-loop dynamics between y_i and u_i depends on not only the single transfer function, g_{ii}, but also the process and controller terms in all other loops. This also implies that tuning of one controller should not be done independently and depends on the other controllers. However, since the controllers include integral actions to avoid offset and the closed-loop dynamics by properly tuned controllers is significantly faster than the open-loop dynamics, a perfect control approximation, $\bar{\mathbf{G}}^i \tilde{\mathbf{G}}_c^i \left(\boldsymbol{I} + \bar{\mathbf{G}}^i \tilde{\mathbf{G}}_c^i\right)^{-1} = \boldsymbol{I}$, can be considered at frequencies lower than the cross-over frequency. Therefore, Eq. 3 can be reasonably simplified in terms of process dynamics excluding controller terms:

$$\begin{aligned} y_i &= \left[g_{ii} - \bar{\mathbf{g}}^{ir} \left(\bar{\mathbf{G}}^i\right)^{-1} \bar{\mathbf{G}}^i \tilde{\mathbf{G}}_c^i \left(\mathbf{I} + \bar{\mathbf{G}}^i \tilde{\mathbf{G}}_c^i\right)^{-1} \bar{\mathbf{g}}^{ic} \right] u_i \\ &= \left[g_{ii} - \bar{\mathbf{g}}^{ir} \left(\bar{\mathbf{G}}^i\right)^{-1} \bar{\mathbf{g}}^{ic} \right] u_i \\ &= g_{ii}^{eff}\, u_i \end{aligned} \tag{4}$$

where the EOTF of loop i, g_{ii}^{eff}, consists of process dynamics term only.

Let us define the effective open-loop transfer function (EOTF) of loop i as the transfer function relating u_i with y_i where loop i are open while all the other loops are closed. It is clear that the EOTF is different from the original open-loop transfer function because of process interaction. A multi-loop MIMO system can be considered as a set of n independent SISO systems with the corresponding EOTFs.

Furthermore, this EOTF can be compactly expressed in terms of dynamic relative gain array (DRGA) [7-9] by using some algebra as follows:

$$g_{ii}^{eff} = \frac{g_{ii}}{\Lambda_{ii}} \tag{5}$$

where Λ_{ii} denotes the ith diagonal element of the DRGA and is calculated by

$$\Lambda_{ii} = \left[\mathbf{G} \otimes \mathbf{G}^{-T}\right]_{ii} \quad (6)$$

where $\otimes$ is the Hadamard product and $\mathbf{G}^{-T}$ is the transpose of the inverse of $\mathbf{G}$.

In the DRGA, the definition of RGA has been extended to include frequency-dependent terms by replacing the steady-state gains with the corresponding transfer functions. It is clear from Eq. 5 that the *i*th diagonal element of the DRGA implies the ratio of open-loop to effective open-loop transfer functions of loop *i* but under the assumption of perfect control of other loops.

IV. Reduced EOTF for Controller Design

The two input, two output (TITO) multi-delay processes are considered here because they are most commonly encountered in the industrial and chemical. The general stable and square transfer function matrix is represented as

$$\mathbf{G}(s) = \begin{bmatrix} g_{11}(s) & g_{12}(s) \\ g_{21}(s) & g_{22}(s) \end{bmatrix} \quad (7)$$

The DRGA can be obtained from Eq. 6 as

$$\Lambda_{11}(s) = \Lambda_{22}(s) = \left(\frac{g_{11}(s)g_{22}(s)}{g_{11}(s)g_{22}(s) - g_{12}(s)g_{21}(s)} \right) \quad (8)$$

Then, the EOTF model for the first and second equivalent individual loops can be found by using Eq. 5, respectively.

$$g_{11}^{eff}(s) = g_{11}(s) - \frac{g_{12}(s)g_{21}(s)}{g_{22}(s)} \quad (9)$$

$$g_{22}^{eff}(s) = g_{22}(s) - \frac{g_{12}(s)g_{21}(s)}{g_{11}(s)} \quad (10)$$

The resulting EOTF is usually too complicated to be directly used for controller tuning. To circumvent this awkwardness, it needs to be simplified to a reduced order model such as the first order plus dead time (FOPDT) and the second order plus dead time (SOPDT) model using a proper model reduction technique.

Consider a simple model reduction technique to get a reduced model of the EOTF. Consider the model reduction to the FOPDT given by

$$g^{r\_eff} = \frac{Ke^{-\theta s}}{\tau s + 1} \quad (11)$$

Expanding g_{ii}^{eff} in a Maclaurin series in s term gives

$$g_{ii}^{eff}(s) = a_{ii} + b_{ii}s + c_{ii}s^2 + O(s^3) \quad (12)$$

The coefficients of this polynomial can be defined by

$$a_{ii} = g_{ii}^{eff}(0) \quad (13)$$

$$b_{ii} = \left.\frac{dg_{ii}^{eff}(s)}{ds}\right|_{s\to 0} \quad (14)$$

$$c_{ii} = \frac{1}{2}\left.\frac{d^2 g_{ii}^{eff}(s)}{ds^2}\right|_{s\to 0} \quad (15)$$

Expanding the FOPDT model given by Eq. 11 in a Maclaurin series in s term also gives

$$g^{r\_eff}(s) = K - K(\theta+\tau)s + K\left[\frac{1}{2}\theta^2 + (\theta+\tau)\tau\right]s^2 + O(s^3) \quad (16)$$

where K, τ, and θ should be identified to approximate g_{ii}^{eff} as close as possible for important frequency ranges. Comparing the first, second, and third term of Eq. 12 with those of Eq. 16 leads to

$$K = a_{ii} \quad (17)$$

$$\tau = \frac{1}{a_{ii}}\sqrt{2c_{ii}a_{ii} - b_{ii}^2} \quad (18)$$

$$\theta = -\frac{b_{ii}}{a_{ii}} - \tau \quad (19)$$

It should be noted that both τ and θ must have positive values. If the dynamics due to process interaction is too complicated to be expressed by the FOPDT, either τ or θ might have the negative values. In this case, a higher order model such as the SOPDT has to be considered as a reduced model of EOTF.

V. Multi-loop PID Controller Design

Once the reduced EOTF is obtained, any PID tuning method for SISO system can be applied to design of multi-loop PID controller design. In this study, the IMC- PID tuning approach is selected. The IMC-PID design approach is commonly used for PID controller tuning in the process industries because it is not only simplicity, but also great improved performance of overall control systems in case of set-point tracking. Therefore, the analytically derived IMC-PID tuning methods have attracted attention of academic and industrial users for many decades, and the IMC-PID tuning rules suggested by Lee et al. [10], which were shown the performance superiorly when compared with other methods, is utilized for the design of each individual PI/PID controller. The procedure is shown as follows: first consider the process model, $G_{eip}(s) = p_A p_M$, where p_A and p_M are the all-pass portion and minimum phase portion, respectively. The conventional IMC filter, f, is selected to ensure the perfect set-point tracking of steps as $f_i(s) = \frac{1}{(\lambda_i s + 1)^n}$, in which λ_i is a design parameter that provides the tradeoff between performance and robustness. Besides, it is the desired closed-loop time constant for set-point tracking. The filter order n is selected as positive integer so that controller is proper and realizable.

The ideal controller G_{ci} that yields the desired loop response perfectly is given by

$$G_{ci} = \frac{q_i}{\left(1 - g^{r\_eff} q_i\right)} = \frac{p_{Mi}^{-1}(s)}{(\lambda_i s + 1)^n - p_{Ai}(s)} \quad (20)$$

where q_i is the IMC controller and is designed by $q_i = p_{Mi}^{-1} f_i$.

The controller obtained directly by Eq. 20 is impractical and it does not have the standard PI/PID form. Hence, the practicable form is required to approximate the PI/PID controller.

Here, the mathematical Maclaurin series is considered first to expanded the ideal controller given by Eq. 20.

$$G_{ci} \equiv \frac{f(s)}{s} = \frac{1}{s}\left[f(0) + f'(0)s + \frac{f''(0)}{2!}s^2 + \frac{f'''(0)}{3!}s^3 + \dots \right] \tag{21}$$

The target is to create the resulting controller in term of the standard PID controller. To do that the G_{ci} in Eq. 20 should be transformed into the equivalent form of the standard PID controller by using Pade approximation. The conventional PID controller parameters can be obtained respectively by

$$K_{ci} = f_i'(0) \tag{22}$$

$$\tau_{Ii} = \frac{f_i'(0)}{f_i(0)} \tag{23}$$

$$\tau_{Di} = \frac{f_i''(0)}{2 f_i'(0)} \tag{24}$$

Again, it is apparent from the above equation that τ_{Ii} and τ_{Di} can be negative due to a major limitation of IMC theory and this potential problem can be avoided by selecting the closed-loop time constant or the appropriate PID controller form.

VI. Robustness Index

It is necessary to analyze the robust stability of multi-loop control system in presence of process uncertainties so that the tuning constraints for the design parameters λ_i of proposed controllers can be ascertained by following the robust stability that published by William [11]. Basically, the control system will be examined under the output multiplication uncertainty. For the multi-delay process with the output multiplicative uncertainty of Δ_0, the upper bound of robust stability can be written by

$$\begin{aligned} \gamma = \bar{\sigma}(\Delta_0) &< 1/\bar{\sigma}\left\{ \left[\left(I + \mathbf{G}(j\omega)\tilde{\mathbf{G}}_c(j\omega) \right)^{-1} \mathbf{G}(j\omega)\tilde{\mathbf{G}}_c(j\omega) \right] \right\} \\ &< \underline{\sigma}\left[I + \left(\mathbf{G}(j\omega)\tilde{\mathbf{G}}_c(j\omega) \right)^{-1} \right], \quad \forall \omega \geq 0 \end{aligned} \tag{25}$$

where $\mathbf{G}(j\omega)\tilde{\mathbf{G}}_c(j\omega)$ is invertible.

For tracking error reduction, disturbance rejection, and insensitivity to plant parameter variations, γ should be as small as possible. Basically, since γ is kept smaller at over frequency ranges, the output responses provide better performance. Inversely, for enhanced robust stability, γ should be kept as large as possible at over frequency ranges.

VII. Simulation Study

Example 1. Wood and Berry (WB) column.

The pilot-scale distillation column model, the eight-tray plus re-boiler separating a mixture of methanol and water, is introduced by Wood and Berry [12]. This model can be represented in term of the transfer function matrix as

$$G(s) = \begin{bmatrix} \dfrac{12.8e^{-s}}{16.7s+1} & \dfrac{-18.9e^{-3s}}{21s+1} \\ \dfrac{6.6e^{-7s}}{10.9s+1} & \dfrac{-19.4e^{-3s}}{14.4s+1} \end{bmatrix} \tag{26}$$

By using Eqs. 9 and 10, the EOTF of each loop can be obtained by

$$g_{11}^{\text{eff}}(s) = \frac{12.8e^{-s}}{16.7s+1} - \frac{6.36(14.4s+1)e^{-7s}}{(21s+1)(10.9s+1)}$$

$$g_{22}^{\text{eff}}(s) = \frac{-19.4e^{-3s}}{14.4s+1} + \frac{9.75(16.7s+1)e^{-9s}}{(21s+1)(10.9s+1)}$$

Accordingly Eqs. 17, 18, and 19, the reduced EOTF model for each individual loop is found as follows

$$g_{11}^{r\_eff} = \frac{6.37e^{-0.31s}}{(10.53s+1)} \;;\; g_{22}^{r\_eff} = \frac{-9.66e^{-4.27s}}{(6.27s+1)}$$

Figure 2 depicts the Bode diagram of the EOP and the EIP for the comparing the approximation precision of the effective open-loop process and the reduction technique.

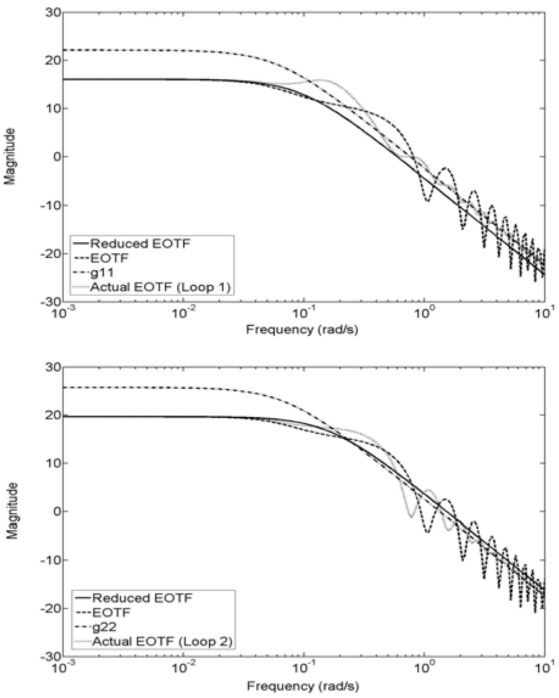

Fig. 2 Bode magnitude plots of the reduced EOTF, the EOTF, g_{ii} and the actual EOTF for WB column.

It is observed from the figure that the magnitudes of Actual EOTF and Reduced EOTF show fairy good coincidence in compared with the closed-loop transfer function for all frequencies. In such a meaning, the proposed method is effectively applied at low and middle frequency, which is the most important case in process control.

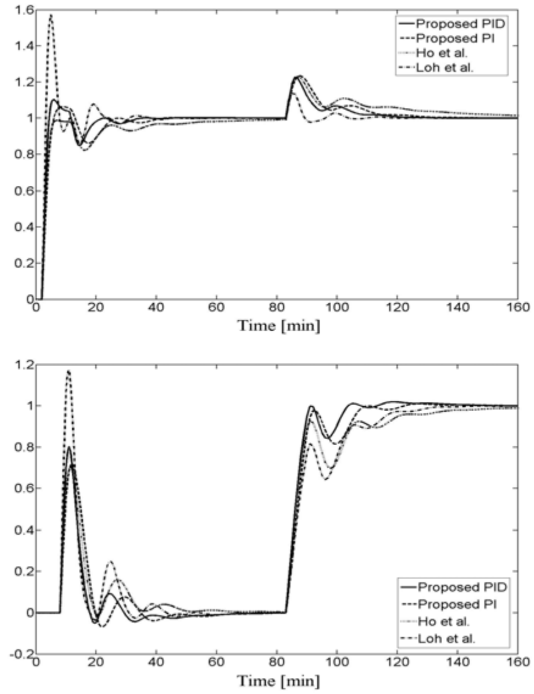

Fig. 3 Closed-loop time responses for WB column.

For a fair comparison, the robust stability level γ should be hold as same as possible for all comparative design methods. The γ value is calculated as 0.47 and 0.33 for Ho et al. [13] and Loh et al. [14], respectively. To cope with the same robust level with Ho's method, in the proposed method, the design parameters λ_i are adjusted directly by using Eq. 25. The closed-loop time responses for the sequential unit step change in set-point are shown in Fig. 3. As one can see from Fig. 3, the proposed PI/PID controllers can be resulted better control performance in contrast with the other two design methods. This conclusion is also convinced by performance indices in Table I.

TABLE I
PI/PID CONTROLLER PARAMETERS AND PERFORMANCE INDICES FOR WB COLUMN

	K_{ci}	τ_{Ii}	τ_{Di}	λ_i	IAE$_t$	γ_i
Proposed PID	0.66 -0.11	10.55 7.54	0.02 1.04	2.2 2.87	19.13	0.47
Proposed PI	0.50 -0.09	10.54 7.32	- -	3.0 4.41	22.5	0.47
Ho et al.	0.57 -0.11	20.7 12.88	- -	- -	29.74	0.47
Loh et al.	0.87 -0.09	3.25 10.40	- -	- -	24.60	0.33

IAE$_t$: total sum of each IAE$_i$

Example 2. Vinante and Luyben (VL) column.

The 24-tray tower separating a mixture of methanol and water is first reported by Luyben [15], and its transfer function matrix can be given by

$$G(s)=\begin{bmatrix} \dfrac{-2.2\,e^{-s}}{7s+1} & \dfrac{1.3\,e^{-0.3\,s}}{7s+1} \\ \dfrac{-2.8e^{-1.8\,s}}{9.5s+1} & \dfrac{4.3e^{-0.35\,s}}{9.2s+1} \end{bmatrix} \tag{27}$$

Consider the same design procedure for above example, the EIP model can be found as follows:

$$g_{11}^{r\_eff} = \frac{-1.35e^{-0.73s}}{(6.61s+1)}; \quad g_{22}^{r\_eff} = \frac{2.65e^{-0.05s}}{(8.84s+1)}$$

It can be easily seen that the VL column system does not exhibit open-loop column diagonal dominance. However, all of J. Lee et al. [16], Lee et al. [17], and Loh et al. [14] design methods can be directly provided the multi-loop controllers for original process by using numerical iteration, IMC-PID analysis, and sequential auto-tuning, respectively. Therefore, the proposed method is compared with those well-known design methods. Accordingly Eq. 25 the proposed PI/PID controller parameters are found since the λ_i values for proposed PI/PID methods are adjusted to obtain the same value of $\gamma = 0.53$ as for both of J. Lee's and Lee's methods. The controller setting parameters and performance indices are shown in Table II.

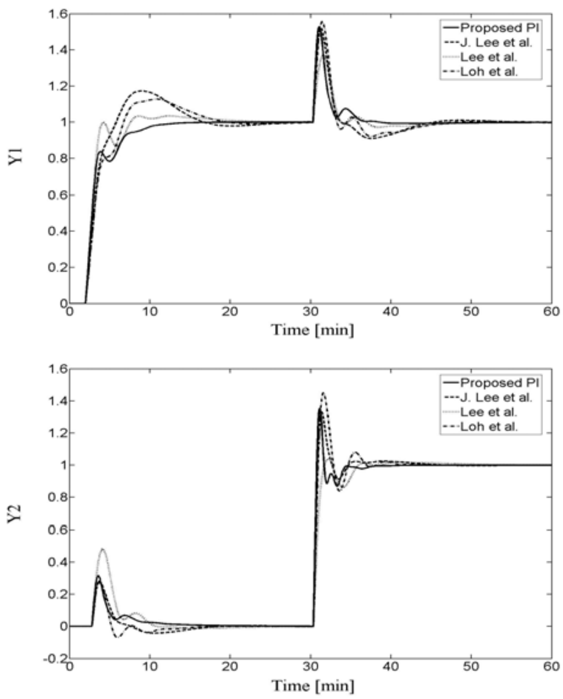

Fig. 4 Closed-loop time responses for VL column.

It is obvious from Fig. 4 that the improved system performance for both proposed PI and proposed PID control systems are clearly demonstrated. In which, the smaller overshoot and faster settling time of proposed output responses compared to that of the above-mentioned design method in term of the unit step change sequentially setting to the binary set-point at t =0 and t = 30. The performance values in Table II clearly point out the advantage of the proposed PI/PID controller over other controllers.

TABLE II
PI/PID CONTROLLER PARAMETERS AND PERFORMANCE INDICES FOR VL COLUMN

	K_{ci}	τ_{Ii}	τ_{Di}	λ_i	$\mathrm{IAE_t}$	γ_i
Proposed PID	-1.83	6.71	0.09	1.98	5.56	0.53
	5.54	8.84	0.002	0.55		
Proposed PI	-1.89	6.72	-	1.89	5.42	0.53
	5.20	8.84	-	0.59		
J. Lee et al.	-1.31	2.26	-	-	7.19	0.53
	3.97	2.42	-	-		
Lee et al.	-1.90	4.48	-	0.74	6.13	0.53
	2.45	5.70	-	0.53		
Loh et al.	-1.35	3.00	-	-	7.28	0.40
	3.36	1.33	-	-		

VIII. CONCLUSION

In this paper, a systematic design of multi-loop PI/PID controller for multi-delay processes is proposed in order to obtain the simplification, flexibility, and effectiveness of decentralized control system. The proposed method can be successfully applied to decompose the complex multi-loop control systems into a number of simple equivalent control loops, in which the dynamic interaction is involved systematically. The multi-loop IMC-PID controller can be designed simply as SISO PI/PID controller for each representative reduction model.

The simulation results show that proposed PI/PID controllers achieved superior performance for several multivariable processes.

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