CONTROLLER DESIGN FOR INTEGRATING PROCESSES IN SISO OR MIMO SYSTEMS

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Abstract: A two-step design to control integrator processes in an SISO or MIMO system is proposed. For an SISO system, the first step of the design is to stabilize the integrator process with P&D modes in a secondary loop to achieve good stability robustness and modest performance. In the second step of design, a P&I controller in the primary loop is derived to improve the overall performance. By this way, an equivalent two-element control system comprising of a single PID control loop and a pre-filter applying on the set-point command is derived. The same design approach is then applied to design multi-loop SISO controllers for MIMO processes, where integrating behavior exists. By employing the same two-step design and the direct method of Huang et al. (2003), 2-df multi-loop PI/PID controllers can be obtained. The Simulation results show that this presented method is effective for both SISO and MIMO process with integrators.

Keywords: Integrating process, two-element control, RGA, Effective open-loop process

1. INTRODUCTION

The integrating processes, serving as material and energy inventory, or, as retention of material for processing and heat transfer, are found in many chemical plants. For years, PID controllers have been used to control such processes. For inventory purposes, usually, proportional controllers with wide proportional bands will be sufficient, but, for tight control purposes, the controller design encounters difficulties due to the existence of integrator and process dead-time. In the past, study of controller design has been mostly focused on open-loop stable processes, until lately, the control of integrating processes starts to attract increasing attentions from the researchers in this field. Many PI or PID controllers have been proposed (Chien and Fruehauf 1990; Tyreus and Luyben, 1992). But, Kwak et al. (2000) showed that a conventional simple feedback system with PI/PID controller will not be able to give the prescribed and desired response unless they use advanced control configuration. Most popular way of design is to use a Smith-predictor type of controller (Kwak, et al., 2001; Chien, et al., 2002; Hang et al., 2003) or use a time-optimal controller (Visioli, 2003). Nevertheless, they are either sensitive to modeling errors or difficult for practical uses. Lately, the control structure incorporating as cascaded loops is also adopted to design control for integrating processes, for examples: Kwak et al. (2000), etc. By the use of the cascaded loops, a two-element control system is resulted. Examples include the PID-P controller of Wang and Cai (2002), and the PI-PD controller of Kaya (2003). Although the resulting performances are slightly poorer than those using predictors, the 2-df controllers are simpler and can be implemented with commercial controller products.

For MIMO processes to be controlled with multiple SISO controllers, the problem becomes more challenging then they are standing alone as SISO loop systems, when the process has integrator(s). Due to the interaction among the loops, the SISO designed controllers are difficult to be stabilized in the MIMO environment. A late work of Huang et al. (2003), decomposes the design of multi-loop controlled MIMO system into that of independent simple SISO loops based on the assumption of open-loop stable dynamics. In order to follow the same design approach for MIMO process with integrator(s), a two-step design approach is thus proposed. In this paper, a design method of multi-loop PI/PID controller to control MIMO processes that have integrators and input dead time is proposed. For SISO controllers in the multi-loop system, a simple two-element controller will be derived. The two-element configuration for the SISO control system is similar to the one of Kaya (2003). The cascaded system is implemented as an equivalent single loop system with a pre-filter at the set-point input (see Figure 1). In the following text, in the first place, a design method for the two-element SISO controller will be derived. Incorporation of this two-element controller design into the design of a multi-loop system will then follow. Guidelines for loop pairing using the RGA analysis are also included.

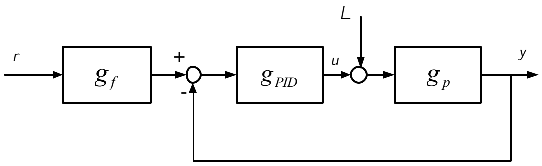

Fig. 1. Two-element control structure

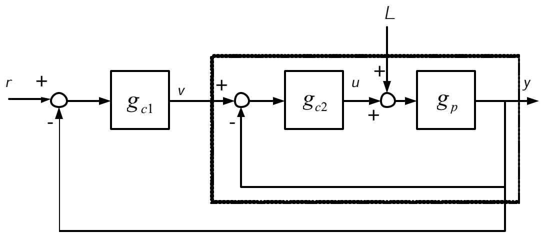

Fig. 2. Equivalent cascaded feedback loop for design.

2. DESIGN FOR TWO-ELEMENT CONTROL SYSTEM

The two-element control system of Fig.1 will be derived as an equivalence to the control configuration in Fig. 2. The design of the internal loop in Fig. 2 is aimed to stabilize the integrating process whose dynamics can be represented by a g_p of the following:

- Process 1

$$g_p(s) = \frac{ke^{-\theta s}}{s} \tag{1}$$

- Process 2

$$g_p(s) = \frac{ke^{-\theta s}}{s(\tau s + 1)} \tag{2}$$

In fact, not only process having integrators, the above transfer functions can represent many slow dynamic processes also. In the cascaded system, a PD controller, $g_{c2}(s)$, is used in the internal loop which stabilizes the integrating processes with sufficient robustness. A PI-type controller, $g_{c1}(s)$, is used to control the resulting closed internal loop (the part boxed by dotted line). The PD and PI controllers used are considered to have the following forms:

$$g_{c1} = k_\beta \left(1 + \frac{1}{\tau_R s}\right) \tag{3}$$

$$g_{c2}(s) = k_\alpha (1 + \tau_D s) \tag{4}$$

Notice that, the product of $g_{c2}(s) g_p(s)$ has an integration mode due to the integrator in $g_p(s)$, and can be written in the following form:

$$g_{lp}(s) = g_{c2}(s) g_p(s) = \kappa(s) \frac{e^{-\theta s}}{s} \tag{5}$$

The PD controllers are selected to compensate for the open-loop transfer functions to become the following standard forms individually, that is:

- For Model 1

$$g_{lp1}(s) = \frac{k_0 (1 + 0.4\theta s) e^{-\theta s}}{\theta s} \tag{6}$$

- For Model 2

$$g_{lp2}(s) = \frac{k_0 e^{-\theta s}}{\theta s} \tag{7}$$

Where, the value of k_0 is chosen as 0.76 in Eq.(6) and 0.6 in Eq.(7) so that each $g_{lp}(s)$ has sufficient gain margin and phase margin. According to the $g_{lp}(s)$ chosen, the parameters of PD controllers are determined. The complementary sensitivity function, $h(s)$, can thus be written as:

$$h(s) = \frac{\kappa(s) \dfrac{e^{-\theta s}}{s}}{1 + \kappa(s) \dfrac{e^{-\theta s}}{s}} \tag{8}$$

Since k_0 is chosen to give modest performance for the internal loop, $h(s)$ in Eq.(8) can be approximated by a first-order plus time delay model, that is:

$$h(s) \cong \frac{e^{-\theta_m s}}{\tau_m s + 1} \tag{9}$$

As θ and k_0 are the only parameters, τ_m and θ_m can be written as functions of these two parameters. As has been studied in the range of θ = 0.2 to 10, the values of τ_m and θ_m for different values of k_0 are shown in Fig. 3 and Fig. 4. The data are also correlated and given in Table 1.

Since the dynamics of the internal loop is represented by an FOPDT model, a PI controller can be used to compensate for the internal loop to become the standard form of Eq. (7).

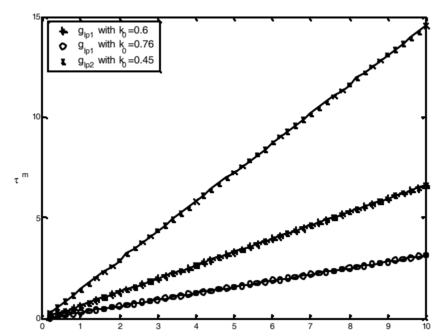

Fig. 3. Comparison of actual values and fitted equations (solid line) for τ_m.

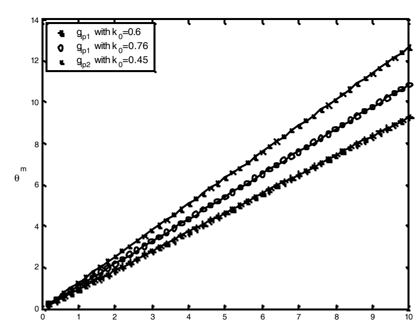

Fig. 4. Comparison of actual values and fitted equations (solid line) for θ_m.

Table 1.FOPDT model parameters of internal closed-loop for different loop transfer function.

Loop transfer function	Loop gain	Time constant	Time delay $\theta = 0.2\sim10$
$g_{lp1}(s)$	0.76	$\tau_m = 0.3139\theta$	$\theta_m = 1.084\theta$
$g_{lp1}(s)$	0.6	$\tau_m = 0.663\theta$	$\theta_m = 0.9264\theta$
$g_{lp2}(s)$	0.45	$\tau_m = 1.452\theta$	$\theta_m = 1.263\theta$

With the cascaded system thus obtained, an equivalent two-element control system consisting of a single loop and a pre-filter at the command input, as shown in Fig. 2, can be derived. They are:

$$g_{PID}(s) = k_c^{'}\left(1+\frac{1}{\tau_R^{'}s}+\tau_D^{'}s\right) \tag{10}$$

$$g_f(s) = \frac{\tau_R^{'}\tau_D^{'}s^2+\tau_R^{'}s+1}{\tau_R^{'}\tau_D^{'}\left(1+\frac{1}{k_\beta}\right)s^2+\tau_R^{'}\left(1+\frac{\tau_R}{k_\beta\left(\tau_R+\tau_D\right)}\right)s+1} \approx \frac{1}{\tau_f s+1} \tag{11}$$

where

$$k_c = k_\alpha + k_\alpha k_\beta\left(\frac{\tau_R+\tau_D}{\tau_R}\right) \tag{12}$$

$$\tau_R^{'} = \tau_R + \tau_D \tag{13}$$

$$\tau_D^{'} = \frac{\tau_R\tau_D}{\tau_R+\tau_D} \tag{14}$$

3 MULTI-LOOP CONTROLLER DESIGN

Consider a n×n system of the following:

$$Y(s) = G(s)U(s) + D(s) \tag{15}$$

where $Y(s)$, $U(s)$ and $D(s)$ designate the output, input, and disturbance vectors, respectively. $G(s)$ is an open-loop transfer function matrix with some of its elements having integrators. Similar to the design approach for SISO systems, an internal controller is used to stabilize the integrating processes first. As show in Fig. 5, $V(s)$ is the input to the secondary loop, and $U(s)$ is the actual control input to the process, and, the resulting internal loop is designated as $\bar{G}(s)$. Assume that $g_{mn}(s)$ (i.e. the element of the (m,n)-th entry of $G_p(s)$) has an integrator, then $G_{c2}(s)$ and $E(s)$ in the internal loop are given as:

$$G_{c2} = \begin{cases} G_{c2}(n,n) = k_{c2,n}(1+\tau_{D2,n}) \\ G_{c2}(i,j) = \delta(i,j), \forall i,j \neq n \end{cases} \tag{16}$$

$$E(i,j) = \delta(i,n)\delta(j,m) \tag{17}$$

where, $\delta(i,j)$ is a kronecker delta function. Substituting $U(s)$ with $V(s)$, Eq. (15) can be written as:

$$Y(s) = G(s)\left(I+G_{c2}(s)EG(s)\right)^{-1}G_{c2}(s)V(s) \tag{18}$$

$$Y(s) = \bar{G}(s)V(s) \tag{19}$$

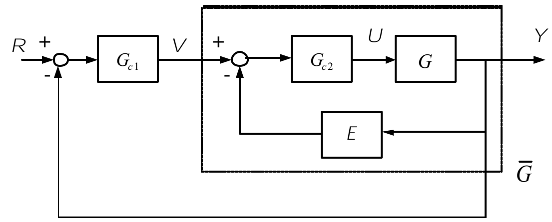

Fig. 5. Multi-loop control structure with inner feedback loops

Because of $G_{c2}(s)$, $\bar{G}(s)$ becomes an open-loop transfer function matrix. To control this $\bar{G}(s)$, the direct method (Huang, et al., 2003) for multi-loop PI/PID controller design can be applied. Before deriving the controllers, first, the pairing of variables has to be addressed.

3.1 Loop pairing

Relative gain analysis has become an accepted method for establish pairs of manipulated and controlled variables to minimize interactions in multivariable systems. However, this RGA computation can't be directly applied to the non-self-regulation system which has integrator in the transfer function matrix. Besides, the allocation of integrators in $G(s)$ will also complicate the pairing problem. As has been mentioned, since integrator is critical to system stability, internal loop(s) is to be used to stabilize the output(s) that has integrator(s) associated with inputs. The choice of pairing for the secondary loops will be clear when each of the output has only one integrator associated with only one manipulating input. But, it becomes more complicated when there are more then one integrator associated with more than one outputs. In the following, the above mentioned different pairing problems will be illustrated using a 3×3 systems. The results can be extended to the n×n systems.

The pairing problem is formulated in the following way:

(1) Assume a candidate set of pairs for constructing the secondary loops. When the secondary loops are closed, the resulting open-loop stable process (i.e. $\bar{G}(s)$) and its steady-state gain, $\bar{\mathbf{K}}$, will be computed, that is:

$$\bar{\mathbf{K}} = \lim_{s\to0}\bar{G}(s) \tag{20}$$

Then, RGA, $\bar{\Lambda}$, is computed from the elements of the resulting $\bar{\mathbf{K}}$ according to:

$$\bar{\Lambda} = \bar{\mathbf{K}} \otimes \left(\bar{\mathbf{K}}^{-1}\right)^T \tag{21}$$

(2) Try the alternative pairing for secondary loops and compute the corresponding RGA, $\bar{\Lambda}$.

(3) Among the candidates of RGAs, find the one which has most comfortable relative gains for pairings. The pairing procedures will thus be discussed for the three occasions as follows.

[Case 1] ***One integrator to one output***

In this case, there is only one possible pair (say, y_a -

u_b) to stabilize the integrator with internal loop. The resulting $\bar{K}$, after closing the internal loop, will have the same $(n-1)\times(n-1)$ sub-matrix as that of K, that is:

$$\bar{K}=\begin{cases}\bar{k}(i,j)=1, & i=a \text{ and } j=b\\ \bar{k}(i,j)=k_{ij}, & i\neq a \text{ and } j\neq b\\ \bar{k}(i,j)=0, & \text{otherwise}\end{cases} \quad (22)$$

In other words, the remaining $(n-1)\times(n-1)$ subsystem can be paired according to the RGA calculated from the corresponding sub-matrix of K.

[Case 2] ***More than one integrators to one output.*** In this case, more integrators are associated with one output. No matter which integrator element is stabilized with a given secondary internal loop, the resulting RGA computing from the resulting $\bar{\mathbf{K}}$ will be the same. In other words, although the choice for pairing the secondary loops may differ, the interaction measure for the remaining sub-system in terms of the RGA will be the same. The proof is given in the following.

Proof. Assume that y_1 is engaged with integrating inputs, and g_{1k} is to be stabilized with an inner loop, we have:

$$u_k=c_{pi,k}(v_k-y_1) \quad (23)$$

$$u_i=v_i;\quad i\neq k \quad (24)$$

$$y_1=\frac{c_{pi,k}g_{1k}}{1+c_{pi,k}g_{1k}}v_k+\sum_{\substack{m=1\\ m\neq k}}^{n}\frac{g_{1m}}{1+c_{pi,k}g_{1k}}v_m \quad (25)$$

$$y_i=\frac{c_{pi,k}g_{ik}}{1+c_{pi,k}g_{1k}}v_k+\sum_{\substack{m=1\\ m\neq k}}^{n}\left(g_{im}-\frac{g_{ik}c_{pi,k}g_{im}}{1+c_{pi,k}g_{1k}}\right)v_m;\quad i\neq 1 \quad (26)$$

According to Eq. (25), the steady-state gains (designate as $\bar{K}^k$) at (1,k) entry, (i.e. $\bar{k}_{1k}$) becomes one. The other gains in the same row (i.e. $\bar{k}_{1j}$, $j\neq k$) becomes $k_{1j}/(k_{c,k}k_{1,k})$ when $g_{1j}(s)$ has integrator, or zero when $g_{1j}(s)$ has no integrator. By Eq. (26), the steady-state gains can be given for i=2~n as $\bar{k}_{ij}=k_{ij}-k_{1j}k_{ik}/k_{1k}$ when $g_{1,j}(s)$ has an integrator, and $\bar{k}_{ij}=k_{ij}$ when $g_{1,j}(s)$ does not have integrator. Similarly, if the g_{1h} is considered to be stabilized with an internal loop, its steady-state gain array $\bar{K}^h$ can be obtained in the same way. It can be shown that $\bar{K}^k$ and $\bar{K}^h$ has the following relation, that is:

$$\bar{K}^k=B\bar{K}^hA \quad (27)$$

where B and A are diagonal matrices:

$$A=\left[a_{ij}\right]=\begin{cases}a_{ii}=-k_{1h}/k_{1k}; & g_{1i}(s)\text{ has an integrator}\\ a_{ij}=0; & i\neq j\\ a_{ii}=1; & \text{otherwise}\end{cases} \quad (28)$$

$$B=\left[b_{ij}\right]=\begin{cases}b_{ii}=k_{ch}/k_{ck}; & i=j=1\\ b_{ij}=1; & i=j\neq 1\\ b_{ij}=0; & i\neq j\end{cases} \quad (29)$$

Then, it is obvious to have:

$$\Lambda^h=\Lambda^kP(h,k) \quad (30)$$

Where, $P(h,k)$ is a permutation matrix which makes h^{th} and k^{th} columns exchanged. As a result, to stabilize the integrating process, there will be no preference to the selection of pairing for secondary loops, as far as the interaction measures for the remaining subsystem is concerned, as the interaction measures for the remaining subsystem will be the same. The guideline for pairing the secondary loops should then be focused on the stability robustness of each individual secondary loop (e.g. choose larger $k_{i,j}$ or faster dynamics).

[Case 3] ***More integrators to more outputs.*** In this case, it can also be shown that stabilizing the integrator element with different secondary loop pairings has the same interaction measures for their sub-systems. Thus, there will be also no preference for one set of candidate pairs over the others, unless the concern of stability in each individual loop is considered. The guideline to pair the secondary loop for integrator, in the first step of design, is thus to focus on each secondary loop to have better stability robustness. In the second step, $\bar{\mathbf{K}}$ and the related RGA of $\bar{G}(s)$ is computed, and, input/output pairs for multi-loop control are determined accordingly.

3.2 Multi-loop controller design

By incorporating the secondary loops, the original MIMO process can be considered as an open-loop stable process. Regarding this resulted open-loop stable process (i.e. $\bar{G}(s)$), multi-loop PI/PID controllers can be designed by employing the direct method proposed by Huang et al. (2003). The transfer function that describes the effective transmission in each equivalent loop is considered as the effective open-loop process (designate as EOP) of that loop. Let $\bar{G}(s)$ and $G_{c1}(s)$ be partitioned into 2×2 form, that is:

$$\bar{G}(s)=\begin{bmatrix}\bar{g}_{1,1} & \bar{G}_{1,2}\\ \bar{G}_{2,1} & \bar{G}_{2,2}\end{bmatrix};\quad G_{c1}(s)=\begin{bmatrix}g_{c,1} & 0\\ 0 & \bar{G}_{c,1}\end{bmatrix} \quad (31)$$

As mentioned, the first equivalent loop (i.e. $\bar{\mathbf{g}}_1$) can be derived as following:

$$\bar{\mathbf{g}}_1=\bar{g}_{1,1}-\bar{G}_{1,2}\bar{G}_{2,2}^{-1}\left\{I-\left(I+\bar{G}_{2,2}\bar{G}_{c,1}\right)^{-1}\right\}\bar{G}_{2,1} \quad (32)$$

All other EOPs can thus be derived in the same way. Huang et al. (2003) provides a approximation formulation to include the effect of $\bar{G}_{c1}(s)$, without knowing exactly what they are, in the formulation of EOPs. As a result, the design of controllers for the EOPs can be carried out independently. Notice that, for each EOP that has integrator in its internal loop, only PI-type controller will be assigned. Other than these loops, PID-type controller will be used to improve each single loop control for the EOPs. The EOPs in Eq. (32), in general, are represented by either the FOPDT or the SOPDT models of the following:

- FOPDT dynamics:

$$\bar{\mathbf{g}}^*=\frac{k_pe^{-\theta s}}{\tau s+1} \quad (33)$$

- SOPDT dynamics (overdamped):

$$\bar{\mathbf{g}}^*=\frac{k_p(\tau_3s+1)e^{-\theta s}}{(\tau_1s+1)(\tau_2s+1)} \quad (34)$$

- SOPDT dynamics (underdamped):

$$\overline{\mathbf{g}}^* = \frac{k_p(\tau_3 s+1)e^{-\theta s}}{\tau^2 s^2 + 2\tau\zeta s + 1} \qquad (35)$$

Methods to determine FOPDT models can be derived from ultimate gains and ultimate frequency, or, by formulating the following optimization problem. That is:

$$Arg\{\mathrm{P}\} = \min_{\mathrm{P}} \int_0^{w_f} \left\{ \left| \mathrm{Re}\left(\overline{\mathbf{g}}(w;\mathrm{P}) - \overline{\mathbf{g}}^*(w;\mathrm{P})\right) \right|^2 + \left| \mathrm{Im}\left(\overline{\mathbf{g}}(w;\mathrm{P}) - \overline{\mathbf{g}}^*(w;\mathrm{P})\right) \right|^2 \right\} dw \qquad (36)$$

where P consists of parameters in $\overline{\mathbf{g}}^*$ and w_f is the frequency bandwidth concerned. Upon finishing the modeling for EOPs, PI and PID controllers can be selected to compensate for the loop transfer functions to become the desired loop transfer functions. Notice each loop gain can be assigned to weight the importance of each loop. For equal weight consideration, the value for each loop is defaulted to be taken as 0.6 for $g_{lp1}(s)$ and 0.45 for $g_{lp2}(s)$. Notice that there is no need to go through an iteration process to determine the final multi-loop controller, the one obtained for the EOP of Eq.(32) will be the one to use.

4. SIMULATION RESULTS

4.1 Example for SISO system

Example 1 Consider a process with the transfer function $0.0506e^{-6s}/s$, which was also given in the paper of Kaya (2003). The PI-PD controller parameters in that paper are $K_c = 1.6184$, $T_i = 17.599$, K_f=1.0956 and T_d=2.4528. Then for the proposed methods, the required parameters for PI-PD and PID-filter are found: k_α=2.5033, τ_D=2.4, k_β=0.1737, τ_R=1.8834, $k_c^{'}$=3.4922, $\tau_R^{'}$=15.1262, $\tau_D^{'}$=2.0192 and τ_f=11.2810. Simulation results are given in Fig. 6. A unit step set point is introduced at time t=0, and a load disturbance d=-1 is introduced at time t=100. The proposed method gives superior results than the other, especially for the disturbance rejection. Although the approximate filter is slightly degraded in system performance, it is pretty easy for implementation in the factory.

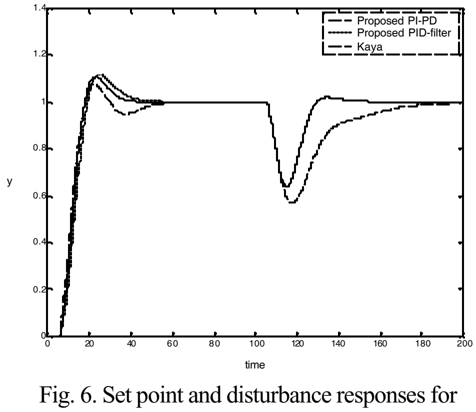

Fig. 6. Set point and disturbance responses for example 1

4.2 Multi-loop controllers design

Example 2. The proposed method is then applied to a system that has three loops. Considered a 3×3 system:

$$G_p = \begin{bmatrix} \frac{-1.986e^{-0.71s}}{s(66.67s+1)} & \frac{5.984e^{-2.24s}}{14.29s+1} & \frac{5.24e^{-60s}}{400s+1} \\ \frac{0.0204e^{-0.59s}}{(7.14s+1)^2} & \frac{2.38e^{-0.42s}}{(1.43s+1)^2} & \frac{-0.33e^{-0.68}}{(2.38s+1)^2} \\ \frac{0.374e^{-7.75s}}{22.22s+1} & \frac{-9.81e^{-1.59s}}{11.36s+1} & \frac{-11.3e^{-3.79s}}{(21.74s+1)^2} \end{bmatrix} \qquad (37)$$

where $g_{1,1}(s)$ isn't a pure integrating process which has an extra first order lag. Since only $g_{11}(s)$ has an integrator, the internal loop pairing should direct to the (1,1)-pair. The inner controller then is designed according to $g_{lp2}(s)$. The pairing for the remaining subsystem is then conducted by the computed RGA of $\overline{\mathbf{K}}$. After pairing the loops, the resulting dynamic models of the EOPs are given in Table 2. Based on these models, the PI and PID controllers are synthesized and are given in the same table. Simulation results for step changes are given in Fig. 7. The results show the performance of these loops is satisfactory.

5. CONCLUSION

In this paper, a two-element control system is applied to design the control for integrating process in either SISO, or MIMO system. For a single-loop system, a two-element control having a PID controller in the feedback loop and a pre-filter at the commend input is resulted. In a MIMO system, the same approach is applied. As a first step, constructing secondary loops to stabilize the integrators is required. Pairing issue for such secondary loops is addressed. It is found that stabilizing an integrator via pairing different input to the same output will result in the same interaction measures for the remaining loops, if the RGA analysis is used. It is also found that loop pairing in the proposed method will have the same result as that of Woolverton (1980). In design, selection of pairing for secondary loops is thus guided by focusing on obtaining the best stability robustness to individual secondary loops, then, the modified steady-state gain matrix and its RGA are computed for the selection of pairs for the remaining loops. A direct method by making use of effective open-loop process (EOP) to design the multi-loop controllers is then used. As a result, controllers in each loop can be designed independently. The effectiveness of this proposed method in designing single-loop and multi-loop controllers is illustrated with two simulated examples, one for a SISO system and one for a 3×3 system. The simulation results from the proposed design give satisfactory control performance for in both cases.

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Table 2. Model of EOP and controller tuning for example 2

	Loop 1	Loop 2	Loop 3
Ultimate frequency	2.2179	1.9263	0.2698
Ultimate gain	2.3494	10.2263	26.8778
Model of EOP	$\frac{e^{-0.9065s}}{0.9585s+1}$	$\frac{2.6665e^{-0.8663s}}{5.2834s+1}$	$\frac{-12.6603e^{-5.96s}}{99.5531s+1}$
Controller	$-11.03\left(1+\frac{1}{69.64s}+2.85s\right)$	$1.37\left(1+\frac{1}{5.28s}\right)(1+0.35s)$	$-0.79\left(1+\frac{1}{99.55s}\right)(1+2.38s)$
Pre-filter	$\frac{1}{1.86s+1}$		

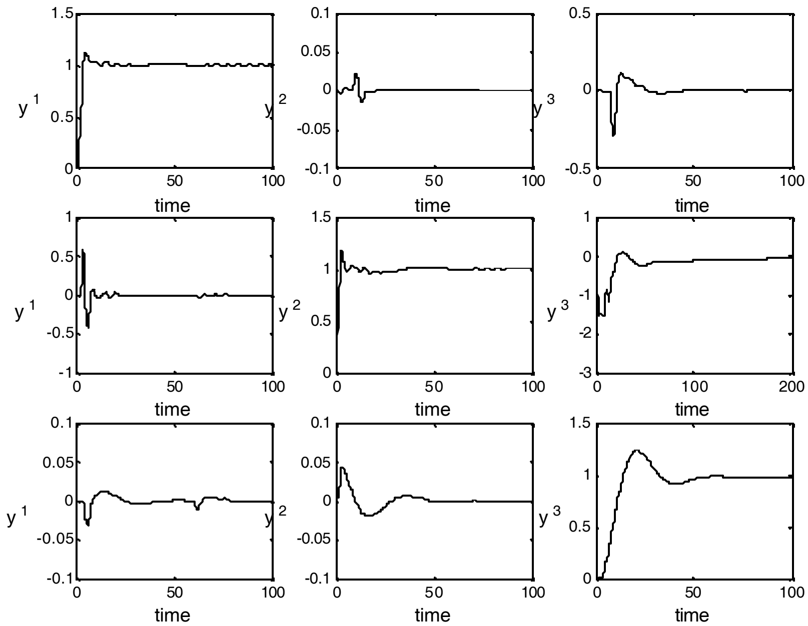

Fig. 7. Responses of multi-loop control for example 2.

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