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Generalized Inverted Decoupling for TITO processes

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Abstract: This paper presents a generalization of inverted decoupling for TITO (two inputs, two outputs) processes that allows more flexibility choosing the transfer functions of the decoupled apparent process. The possible configurations and their corresponding different cases are analyzed. In order to select the proper configuration, the realizability conditions are exposed. The methodology is applied to a simulation example and a real experimental lab process. Comparisons with other authors show its effectiveness.

1. INTRODUCTION

Generally, most industrial processes are multivariable systems. Two-input two-output (TITO) system is one of the most prevalent categories of multivariable systems, because there are real processes of this nature, or because a complex process has been decomposed in 2×2 blocks (Åström *et al.*, 2002), (Vázquez *et al.*, 1999) with non negligible interactions between its inputs and outputs. When the interactions in different channels of the process are modest, a diagonal controller (decentralized control) is often adequate. Nevertheless, when interactions are significant, a full matrix controller (centralized control) is advisable.

There are two approaches of centralized control: a pure centralized strategy (Wang *et al.*, 2002), (Wang *et al.*, 2003), (Xiong *et al.*, 2007), (Morilla *et al.*, 2008) or a decoupling network D(s) combined with a diagonal decentralized controller C(s) (Nordfeldt *et al.*, 2006), (Tavakoli *et al.*, 2006), (Cai *et al.*, 2008). The last of them uses the decoupling network to reduce the existing process interaction, allowing for independent control of the loops. The controller C(s) sees the apparent process Q(s)=G(s)·D(s) as a set of completely independent processes.

Most decoupling approaches use a conventional decoupling scheme in which the process inputs are derived by a time-weighted combination of feedback controller outputs (Fig. 1). In this case the design of the decoupler network is obtained from (1), generally specifying two elements of the decoupler or the two desired transfer functions of the apparent process. This approach has received considerable attention in both control theory and industrial practice for several decades. The most extended forms of conventional decoupling were termed ideal and simplified decoupling in (Waller, 1974).

$$D(s) = G^{-1}(s)\cdot Q(s) \tag{1}$$

Although it is rarely mentioned in the literature, there is an alternative means of decoupling, called inverted decoupling, that derives a process input as a time-weighted combination of one feedback controller output and the other process inputs (Fig. 2). In this case, it is possible to keep the same apparent process of ideal decoupling while using the simple decoupler elements of simplified decoupling (Wade, 1997). In (Gagnon *et al.*, 1998), a comparative study of simplified, ideal and inverted decoupling is presented. (Chen *et al.*, 2007) improved upon the inverted decoupling technique for a class of stable linear multivariable processes with multiple time delays and non-minimum-phase zeros.

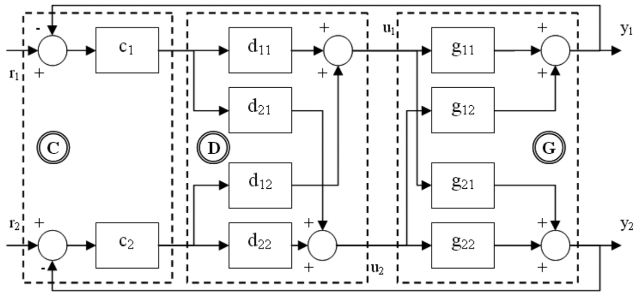

Fig. 1. 2x2 conventional decoupling scheme

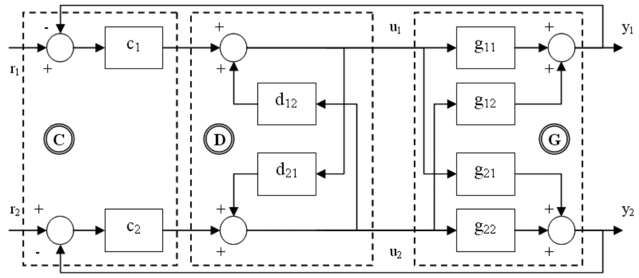

Fig. 2. 2x2 inverted decoupling scheme

All these papers use the inverted decoupling scheme of Fig. 2 with only two elements different from the unity. However, this work presents a generalized inverted decoupling scheme with four decoupler elements (Fig. 3), that allows more flexibility choosing the transfer functions of the decoupled apparent process Q(s). In addition, all possible cases choosing two elements equal to unity are studied. Section 2 shows the corresponding expressions for this generalized inverted decoupling. In Section 3, realizability conditions are stated and some rules are advised to select the proper configuration. In Section 4 the performance of the proposed methodology is tested and compared with other authors. Finally, conclusions are commented in Section 5.

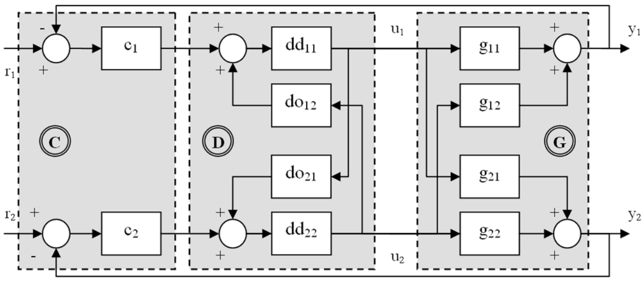

Fig. 3. 2x2 generalized inverted decoupling scheme (configuration A)

2. GENERALIZED 2x2 INVERTED DECOUPLING

In order to study the generalized inverted scheme of Fig. 3, a matrix representation is proposed as it is shown in Fig. 4. There are two elements of the decoupler (Dd(s) matrix) which try to connect directly the decoupler inputs *m* with the process inputs *u*, while the other two elements (Do(s) matrix) feed back the input process *u* toward the decoupler inputs in order to decouple the system.

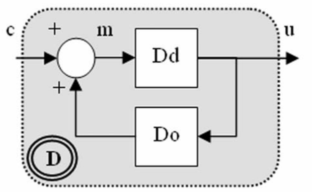

Fig. 4. Matrix representation of inverted decoupling

The whole decoupler D(s) is split into two matrices: a matrix Dd(s) in the direct path (between controller outputs *c* and process inputs *u*) and a matrix Do(s) in a feedback loop (between process inputs *u* and controller outputs *c*). The Dd(s) matrix must have only two non-zero elements, since there must be only a direct connection for each process input. Note that these relationships are not required in the Do(s) matrix. Additionally, since the signal flow direction in Do(s) is opposite that of Dd(s), the corresponding elements of Do(s) that must equal zero are the transpose non-zero elements of Dd(s).

Following the decoupler representation given in Fig. 4, the expression of the whole decoupler matrix D(s) is obtained as follows:

$$D(s)=Dd(s)\cdot(I-Do(s)\cdot Dd(s))^{-1} \tag{2}$$

The transfer function matrix D(s) of conventional decoupling is related to the inverted decoupling structure according to (2). As it is a complex expression, it is easier to work with its inverse, which is very simple, as follows:

$$D^{-1}(s)=(I-Do(s)\cdot Dd(s))\cdot Dd^{-1}(s)=Dd^{-1}(s)-Do(s) \tag{3}$$

Inverting equation (1) and substituting it into (3), the following expression is obtained:

$$Dd^{-1}(s)-Do(s)=Q^{-1}(s)\cdot G(s) \tag{4}$$

This last expression can be used to calculate the elements of the inverted decoupling. Note that Dd(s) has to be non-singular because it is inverted, and therefore, when its elements are chosen, only one element in each row and column can be selected. Consequently, there are only two possible choices of Dd(s), which leads to two different configurations: diagonal elements (configuration A) or off-diagonal (configuration B).

2.1 Configuration A

With this configuration, the following expressions (6) for the elements of the inverted decoupling are obtained from (5), which is derived from (4). These are the expressions for general inverted decoupling with configuration A. $q_1(s)$ and $q_2(s)$ are the desired equivalent open loop transfer functions to be controlled by the decentralized control, and they can be specified freely as long as the decoupler elements are realizable. However, in most examples found in the literature on inverted decoupling, two of these elements are set to unity, and so only two elements need to be implemented.

$$\begin{pmatrix} \frac{1}{dd_{11}} & -do_{12} \\ -do_{21} & \frac{1}{dd_{22}} \end{pmatrix} = \begin{pmatrix} \frac{g_{11}}{q_1} & \frac{g_{12}}{q_1} \\ \frac{g_{21}}{q_2} & \frac{g_{22}}{q_2} \end{pmatrix} \tag{5}$$

$$dd_{11}=\frac{q_1}{g_{11}} \qquad do_{12}=\frac{-g_{12}}{q_1} \qquad do_{21}=\frac{-g_{21}}{q_2} \qquad dd_{22}=\frac{q_2}{g_{22}} \tag{6}$$

Usually, the two non-zero elements equal to one are the elements in the direct way, that is, the elements of the Dd(s) matrix. However, this case is only one of the four possible cases according to the two elements chosen to be equal to unity. Nevertheless, the realizability of the decoupler elements in each configuration is always the same, independent of the selected case. For example, as shown in Table 1, for inverted decoupling of TITO processes using configuration A, the pair of decoupler elements that differ from one have the following expressions:

$$\frac{-g_{12}}{g_{11}} \quad \text{and} \quad \frac{-g_{21}}{g_{22}} \tag{7}$$

In any case, the main advantage of (6) is the simplicity of the decoupler elements in comparison with the corresponding expressions (8) for the conventional decoupling scheme. The decoupler elements of (6) do not contain sum of transfer functions, whereas the controller elements of (8) may result very complicated even if the elements of the system have simple dynamics. In addition, the apparent processes $q_i(s)$

may keep very simple in such a way that simple tuning rules can be used for the decentralized controller.

$$D = \begin{pmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{pmatrix} = \frac{\begin{pmatrix} g_{22}q_1 & -g_{12}q_2 \\ -g_{21}q_1 & g_{11}q_2 \end{pmatrix}}{g_{11}g_{22}-g_{12}g_{21}} \quad (8)$$

Table 1. Cases of inverted decoupling with two unitary elements (configuration A)

	Decoupler elements	Decoupled process
Case 1	$dd_{11}=dd_{22}=1$ $do_{12}=\frac{-g_{12}}{g_{11}}$, $do_{21}=\frac{-g_{21}}{g_{22}}$	$Q=\begin{pmatrix} g_{11} & 0 \\ 0 & g_{22} \end{pmatrix}$
Case 2	$dd_{11}=do_{21}=1$ $do_{12}=\frac{-g_{12}}{g_{11}}$, $dd_{22}=\frac{-g_{21}}{g_{22}}$	$Q=\begin{pmatrix} g_{11} & 0 \\ 0 & -g_{21} \end{pmatrix}$
Case 3	$do_{12}=do_{21}=1$ $dd_{11}=\frac{-g_{12}}{g_{11}}$, $dd_{22}=\frac{-g_{21}}{g_{22}}$	$Q=\begin{pmatrix} -g_{12} & 0 \\ 0 & -g_{21} \end{pmatrix}$
Case 4	$do_{12}=dd_{22}=1$ $dd_{11}=\frac{-g_{12}}{g_{11}}$, $do_{21}=\frac{-g_{21}}{g_{22}}$	$Q=\begin{pmatrix} -g_{12} & 0 \\ 0 & g_{22} \end{pmatrix}$

Nevertheless, the structure of the inverted decoupling scheme presents an important disadvantage: because of stability problems it cannot be applied to processes with multivariable right half plane (RHP) zeros, that is, RHP zeros in the determinant of the process transfer matrix G(s).

For internal stability, these RHP zeros should appear in open-loop transfer functions. In the conventional decoupling scheme, RHP zeros of the determinant of G(s) can be included into the apparent processes $q_i(s)$. However, it is not possible using inverted decoupling, because such RHP zeros would appear as unstable poles in some decoupler element according to (6). Only if the multivariable RHP zero is associated to an only output, and therefore it is included into the process transfer functions of a same row, inverted decoupling can be applied because the zero will be cancelled.

2.2 Configuration B

In this configuration (off-diagonal elements of Dd(s)), the general expressions (10) for the inverted decoupling are obtained from (9), which is derived from (4). Note that care should be taken in inverting the Dd matrix. The scheme of this configuration is shown in Fig. 5.

$$\begin{pmatrix} -do_{11} & \frac{1}{dd_{21}} \\ \frac{1}{dd_{12}} & -do_{22} \end{pmatrix} = \begin{pmatrix} \frac{g_{11}}{q_1} & \frac{g_{12}}{q_1} \\ \frac{g_{21}}{q_2} & \frac{g_{22}}{q_2} \end{pmatrix} \quad (9)$$

$$do_{11}=\frac{-g_{11}}{q_1} \qquad dd_{12}=\frac{q_2}{g_{21}} \qquad dd_{21}=\frac{q_1}{g_{12}} \qquad do_{22}=\frac{-g_{22}}{q_2} \quad (10)$$

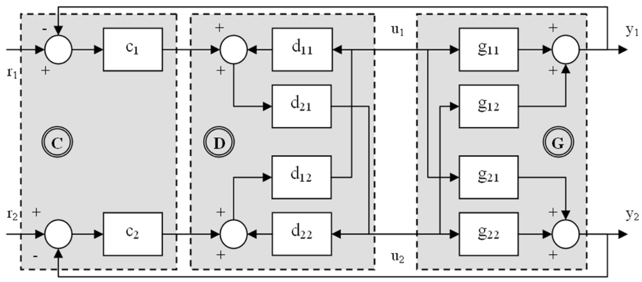

Fig. 5. 2x2 generalized inverted decoupling scheme (configuration B)

If two of these elements are set to unity, there are again four possible cases (as with configuration A). However, the pair of decoupler elements that differ from one is given by (11), which is the inverse of (7) in the other configuration.

$$\frac{-g_{11}}{g_{12}} \quad \text{and} \quad \frac{-g_{22}}{g_{21}} \quad (11)$$

3. DECOUPLER REALIZABILITY

The realizability requirement for any decoupler is that all of its elements must be proper, causal and stable. For processes with time delays or non-minimum-phase zeros, direct calculation of the decoupler can lead to elements with prediction or right-half-plane (RHP) poles. Therefore, essential measures must be taken to deal with them. Next, the conditions that a specified configuration (A or B) needs to satisfy in order to be realizable are commented. Also the constraints on the apparent process transfer function $q_i(s)$ are indicated. There are three aspects to take into account and to be inspected by row:

1 - Non causal time delays τ_{ij} must be avoided in decoupler elements. If g_{ik} is the transfer function of the row *i* with the smallest time delay τ_{ik}, the element dd_{ki} of Dd(s) should be different from zero. In addition, the time delay (τ_i) of the q_i apparent process must be in the range between the minimum and maximum time delays of the same row.

$$\min(\tau_{ij}) \le \tau_i \le \max(\tau_{ij}) \quad j=1,2 \quad (12)$$

where $\tau(f(s))$ represents the time delay of a generic function f(s), *min* represents the minimum function, and *max*, the maximum function.

2 - Decoupler elements must be proper, that is, the relative degrees r_{ij} must be greater or equal than zero. Similarly to the previous case, the element dd_{ki} should be different from zero if the transfer function g_{ik} has the smallest relative degree r_{ik} of the row *i*. In addition, the relative degree (r_i) of the q_i transfer function must fulfil

$$\min(r_{ij}) \le r_i \le \max(r_{ij}) \quad j=1,2 \quad (13)$$

3 - When some transfer function g_{im} has a RHP zero, the element dd_{mi} of Dd(s) should be equal to zero in order to avoid this zero becomes a RHP pole in some decoupler element. When the zero appears in all elements of the same row, it is necessary to check its multiplicity η_{ij} in each element. Again, if g_{ik} is the transfer function of the row *i* with

the smallest RHP zero multiplicity η_{ik}, the element dd_{ki} should be non-zero. This RHP zero must appear in the q_i apparent process with a multiplicity (η_i) that fulfils

$$\min(\eta_{ij}) \le \eta_i \le \max(\eta_{ij}) \quad j = 1,2 \tag{14}$$

From (12), (13) and (14), note that when the value (time delay, relative degree or RHP zero multiplicity) is shared by both transfer functions of the row, there are more possibilities to choose the configuration, but the flexibility (time delay or relative degree) of the apparent process q_i is limited to the common value of row.

When two elements of Dd(s) have to be selected necessarily in the same column to satisfy the previous conditions in both rows, there is no realizable configuration. Then, it is necessary to insert an additional block N(s) between the system G(s) and the inverted decoupler in order to modify the process and to force the non-realizable elements into realizability. Then, inverted decoupling would be applied to the new process $G_N(s)=G(s)\cdot N(s)$.

N(s) is a diagonal block with the necessary extra dynamics. If there are no realizability problems in the row *i*, the N(i,i) element is equal to the unity. If the non-realizability comes from an element with a non causal time delay, an additional time delay ($e^{-\tau s}$) is inserted in the corresponding diagonal element of N(s). If it comes from a RHP zero z, which has become unstable pole, the following element is used in N(s)

$$\left(\frac{-s+z}{s+z^*}\right)^{\eta_i} \tag{15}$$

where z* is the complex conjugate of z. And if it comes from a properness problem, a simple stable pole with the adequate multiplicity can be inserted as follows

$$\frac{1}{(\lambda s+1)^{r_i}} \tag{16}$$

For illustration, considering the following example in (Wang *et al.*, 2002):

$$G(s) = \begin{pmatrix} \dfrac{e^{-2s}}{s+2} & \dfrac{-e^{-6s}}{s+2} \\ \dfrac{(s-0.5)\cdot e^{-3s}}{(s+2)^2} & \dfrac{(s-0.5)^2\cdot e^{-8s}}{2(s+2)^3} \end{pmatrix} \tag{17}$$

This process has a multivariable RHP zero at s=0.5. Nevertheless, it is associated with a single output, the second one, and therefore, inverted decoupling can be applied. However, this RHP zero appears in the two process transfer functions of the second row with different multiplicity. According to the previous RHP zero condition, the element dd_{21} should be selected to be non-zero in the Dd matrix because element G(2,1) has the smallest RHP zero multiplicity. In addition, it has the smallest time delay of the second row. In the first row, due to time delay condition, the element dd_{11} should be selected to be non-zero in the Dd matrix. Since elements dd_{11} and dd_{21} are in the same column, no configuration is initially realizable. To achieve realizability, an extra time delay of 4 units has to be added in the first input. In this case, the new process to be decoupled is given by (18), and using configuration B, the element dd_{12} can be selected in the first row. Then, specifying an apparent process composed by off diagonal elements of (18) and according to (10), the decoupler matrices are given by (19). The RHP zero appears in the apparent process of the second output, which is necessary for internal stability.

$$G_N(s) = \begin{pmatrix} \dfrac{e^{-6s}}{s+2} & \dfrac{-e^{-6s}}{s+2} \\ \dfrac{(s-0.5)\cdot e^{-7s}}{(s+2)^2} & \dfrac{(s-0.5)^2\cdot e^{-8s}}{2(s+2)^3} \end{pmatrix} \tag{18}$$

$$Dd=\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad Do=\begin{pmatrix} 1 & 0 \\ 0 & \dfrac{-0.5(s-0.5)\cdot e^{-s}}{(s+2)} \end{pmatrix} \tag{19}$$

Generally it is preferable to add the minimum extra dynamics. Therefore, after checking the necessary additional dynamics of each configuration (Fig. 3 or Fig. 5), it is chosen that one with less RHP zeros or time delays in N(s).

4. EXAMPLES

In this section the proposed methodology is applied to a simulation process and its effectiveness is also verified in a real quadruple tank plant.

4.1 Example 1: Vinante-Luyben distillation column

The Vinante-Lyuben distillation column (Cai *et al.*, 2008) is a multivariable system with important delays and it is described by the transfer matrix (20). Due to time delays, no configuration is initially realizable, and therefore, it is necessary to insert an extra delay of 0.7 units in the second input. The element of N(s) is $n_2(s)=e^{-0.7s}$. Then, the new apparent process to be decoupled would be given by (21). According to the conditions of Section 3, configuration A should be chosen.

$$G_V(s) = \begin{pmatrix} \dfrac{-2.2e^{-s}}{7s+1} & \dfrac{1.3e^{-0.3s}}{7s+1} \\ \dfrac{-2.8e^{-1.8s}}{9.5s+1} & \dfrac{4.3e^{-0.35s}}{9.2s+1} \end{pmatrix} \tag{20}$$

$$G_V^N(s) = \begin{pmatrix} \dfrac{-2.2e^{-s}}{7s+1} & \dfrac{1.3e^{-s}}{7s+1} \\ \dfrac{-2.8e^{-1.8s}}{9.5s+1} & \dfrac{4.3e^{-1.05s}}{9.2s+1} \end{pmatrix} \tag{21}$$

In this example, the proposed generalized inverted decoupling is applied to (21), specifying the apparent process Q(s) given in (22), which is practically the same apparent process used in (Cai *et al.*, 2008) for a normalized decoupling design. The obtained inverted decoupler elements are given by (23). The performance specifications are a gain margin of 3 and a phase margin of 60º, in both loops. In order to achieve the same performance obtained with this normalized decoupling, and because the apparent decoupled processes are practically identical, the same PI parameters are used in the proposed control.

$$Q(s) = \begin{pmatrix} \dfrac{2.0785e^{-s}}{6.691s+1} & 0 \\ 0 & \dfrac{4.4769e^{-1.5935s}}{8.7939s+1} \end{pmatrix} \quad (22)$$

Fig. 6 and Fig. 7 show the closed loop system response of the designed inverted decoupling control in comparison with that of the normalized decoupling of (Cai *et al.*, 2008). A multiloop PID controller for the same specifications and based on the method of (Vázquez *et al.*, 1999) is also shown. The PID parameters for each method are collected in Table 2.

$$\begin{aligned} dd_{11} &= \frac{-14.55s-2.079}{14.72s+2.2} \approx -0.9448 \\ do_{12} &= \frac{-8.698s-1.3}{14.55s+2.079} \\ do_{21} &= \frac{(24.62s+2.8)}{42.53s+4.477}e^{-0.207s} \\ dd_{22} &= \frac{(41.19s+4.477)}{37.81s+4.3}e^{-0.543s} \approx 1.041 \cdot e^{-0.543s} \end{aligned} \quad (23)$$

Table 2. PID parameters for each method in example 1

	Proposed		Normalized		Decentralized	
	loop 1	loop 2	loop 1	loop 2	loop 1	loop 2
Kp	1.76	0.64	1.76	0.64	-1.55	2.65
Ti	3.79	13.62	3.79	13.62	2.5	1.95
Td	0	0	0	0	0.17	0.24

There is a unit step change in the first reference at t=1 min, and at t=40 min, in the second one. At t=70 min, there is a 0.5 step in both process inputs as input disturbances. In the first loop the proposed control achieves the best response. The decentralized control obtains the best performance in the second loop, with fast reference tracking and disturbance rejection. However, the proposed control achieves perfect decoupling, while the others present important interactions.

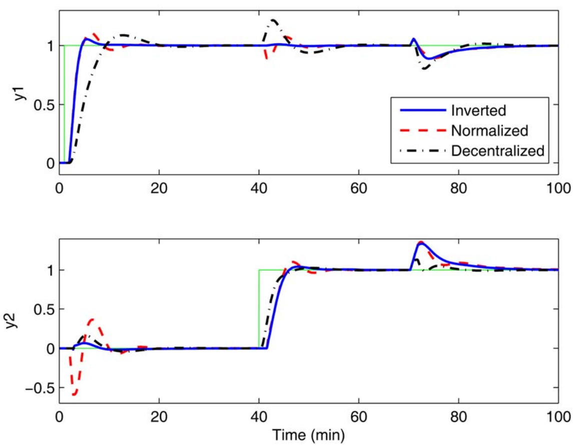

Fig. 6. Outputs of the response of the VL column

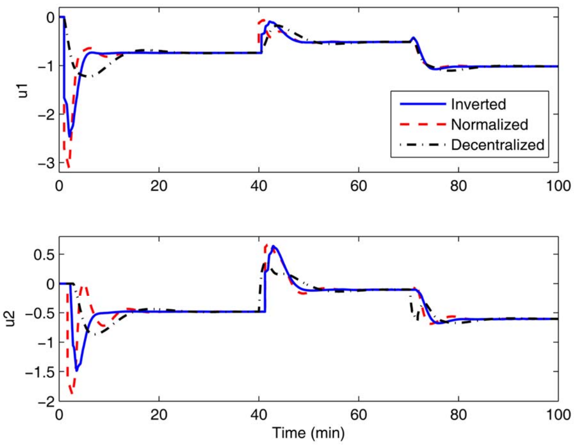

Fig. 7. Control signals of the response of the VL column

The response of the proposed control is better than that of normalized decoupling in (Cai *et al.*, 2008). In addition, although the complexities of both decouplers are similar, another advantage of the proposed decoupling over normalized decoupling is its direct method of carrying out the decoupler network design. In normalized decoupling design, the procedure is slightly more complex with the calculation of the normalized gain matrix, the RNGA and the RARTA.

4.2 Example 2: Experimental quadruple tank process

The real process is a quadruple tank plant (Johansson, 2000) in the lab of the Automatic Control Department of Lund University. The outputs are the level of the lower tanks inside the range of [0-20] cm (or [0-10] V), and the inputs are the flow references of the secondary control loops, in the range of [0-10] V. The plant was configured in order to show interaction problems without having multivariable RHP zeros; and then, the process was identified obtaining the model given in (24), which has a RGA of 2.9.

$$G_T(s) = \begin{pmatrix} \dfrac{1.4}{14.62s+1} & \dfrac{0.97}{(8.63s+1)(12.52s+1)} \\ \dfrac{1.09}{(9.26s+1)(11.96s+1)} & \dfrac{1.15}{13.7s+1} \end{pmatrix} \quad (24)$$

Due to relative degrees, configuration A must be chosen for realizability without adding extra dynamics. If Dd(s) matrix is fixed to the unitary matrix, according to Table 1, the apparent processes $q_1(s)$ and $q_2(s)$ are given by $g_{11}(s)$ and $g_{22}(s)$ of (24), and the other two elements of Do(s) are:

$$\begin{aligned} do_{12}(s) &= \frac{-0.6929 \cdot (14.62 \cdot s+1)}{(12.52 \cdot s+1) \cdot (8.63 \cdot s+1)} \\ do_{21}(s) &= \frac{-0.9478 \cdot (13.7 \cdot s+1)}{(9.26 \cdot s+1) \cdot (11.96 \cdot s+1)} \end{aligned} \quad (25)$$

Two PI controllers were tuned to obtain a phase margin of 60º in both loops limiting the bandwidth frequency around 0.1 rad/s, where the interactions problems of the process are greater. The PI parameters are listed in Table 3.

Table 3. PI parameters for example 2

Loop	Kp	Ti
1	0.54	4.8
2	0.59	4.4

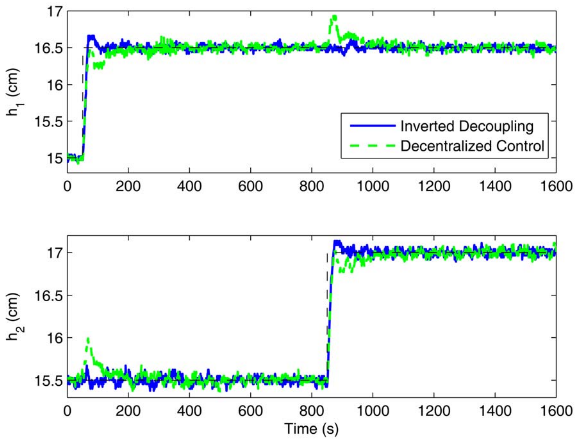

Fig. 8. Outputs of the response of the quadruple tank process

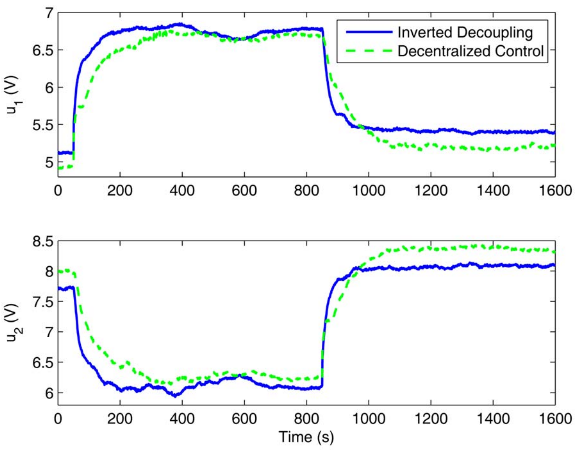

Fig. 9. Control signals of the response of the quadruple tank process

Fig. 8 and 9 show the resultant response of the closed loop system for a step of 1.5 cm in the references. For comparison, we also show the response of the decentralized controller obtained only with the PI controllers in Table 3, without the decoupler elements (25). Therefore, it is like two independent SISO controllers, one for $g_{11}(s)$ and the other for $g_{22}(s)$. With inverted decoupling, a better response is achieved with a very good decoupling performance and a smaller settling time in both loops. The decentralized control reaches the references later, and the rejection of the interactions is very slow.

5. CONCLUSIONS

A new generalized approach of the inverted decoupling technique for 2x2 processes has been developed in this work. The problem is approached from a compact matrix formulation, in such a way that the procedure could be extended easily to nxn systems. In addition, the methodology allows for more flexibility in choosing the decoupled apparent processes, and since they are usually very simple, the tuning of decentralized controllers is much easier.

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