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Integration of Pairing Elimination Methods for Achieving the Best Control Structure in ALSTOM Gasifier

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Key words: Component; criteria of selecting pairing; DIC; minimal interaction; RGA; three operating point of ALSTOM Gasifier

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Abstract: This study is contributed to choose a suitable pairing for using in decentralized controller for the ALSTOM Gasifier benchmark process. The selected pairing should have DIC attribute, minimum interaction and compatibles with chemical laws and RGA. To achieve this aim, five necessary DIC criteria are inspected and inappropriate pairings are eliminated. Afterwards, those pairing that are not realistically implementable are removed. Finally, the remained pairings are sorted with respect to interaction values and RGA and then appropriate pairing is chosen. There is no pairing that is DIC in all three operating points, nevertheless a pairing is suggest that is DIC and realistically implementable in operating points 50 and 100%.

INTRODUCTION

Coal is one of the main power source in the world that despite of its environmentally issues is using broadly. To surmount these environmentally problems and efficient power generation from coal, Gasifier developed (originally by British Clean Coal Technology Development Division) that based on spouted fluidized-bed gasification concept can gasify coal with air and steam[1]. The ALSTOM Power Technology Centre issued an open challenge in 1997 to control of a Gasifier plant[2]. In this benchmark, the Gasifier is define as a multivariable, non-linear system, having five inputs (coal, limestone, air, steam and char extraction) and four outputs (pressure, temperature, bed mass and gas quality) with a high degree of interaction between them. In addition, there is a disturbance input PSINK representing pressure disturbances which would vary according to the position of the gas turbine fuel valve.

The benchmark has particular objectives: first, a controller must be designed that in the presence of step pressure disturbance, fulfills some specification on the system outputs, inputs and input rates, based on a linearized model of the system at the 100 percent load operating point. Second, this controller can reject a sine wave pressure disturbance at 100, 50 and 0 percent load operating point. Also the controller must be in such a way that can evaluated the system in these operating point.

There are a variety of controllers that can be used to achieve these desire specifications such as MPC[3] H_2[4], Self-adaptive Differential Evolution algorithm[5], PIP[6], decentralized controller and so on. Decentralized controller have several advantages over multivariable controller such as Flexibility in Operation, Failure Tolerance, Simplified Design and Simplified Tuning[7] and are robust and relatively simple to understand and to change[8]. For these reason, it is preferred to multivariable controller in large scale systems and

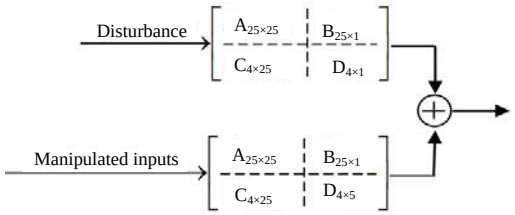

Fig. 1: Division of system into two split subsystems

industrial processes. To use decentralized controller, it is needed to determine most favorable pairing between inputs and outputs. For this purpose, Relative Gain Array (RGA)[9] can be used. The linearized system has some poles close to imaginary axis such that the bed-mass drifts from the steady state value. Nevertheless, the steady state RGA of a system with open loop integrators cannot be calculated so, a standard RGA analysis of the Gasifier is likely not to be accurate[5]. This effect in disregarded in many of the previous control system designs on the Gasifier[4, 10, 11]. Another technique like GRDG can be employed in order to determine appropriate pairing as well as disturbance rejection[12].

In this study, for choosing the suitable pairings on three operating points, chemical laws, interaction measure and Decentralized Integral Controllability (DIC)[8] criteria is considered, that extra to RGA, have additional rules to eliminate inappropriate pairings.

State space model of initial system, without any state reduction, has 25 states. Dimensions of state space matrices are: $A^{25\times25}$, $B^{4\times25}$, $C^{4\times25}$, $D^{4\times6}$.

Separation of input disturbance affect from main transfer function: Since, the disturbance that is considered as a system input is not manipulatable, the system can be decomposed into two split subsystems that inputs to one of them are desired control command and to other one is the disturbance. Thereupon the output of system is sum of two subsystems outputs. A schematic of these two split subsystems is shown in Fig. 1.

Two methods have been used to separation of main system which are illustrated in following sections and at last, advantages of them is discussed.

FIRST METHOD: USING TRANSFER FUNCTION

As mentioned before, the main transfer function is composed of a matrix with four columns and six rows which sixth column is connected to input disturbance. Therefore, disturbance transfer function can be achieved by:

$$G_{Dist} = G(:,6) \tag{1}$$

Second method: using state-space matrix: The sixth column of matrices B and D connected to disturbance input. Consequently, for obtain a state-space model which its input is only disturbance, the sixth column of matrices B and D are used as B_{Dist} and D_{Dist}, respectively. The state-space model that connected only to disturbance would be:

$$A_{Dist} = A \tag{2}$$

$$B_{Dist} = B(:,6) \tag{3}$$

$$C_{Dist} = C \tag{4}$$

$$D_{Dist} = D(:,6) \tag{5}$$

The advantage of the second method over the first, is achieving state space matrix. Nevertheless, using transfer function which obtains in first procedure, state-space matrices can be attained but precision of this method is less than direct method. Also numbers of states can change.

ELIMINATING LIME (FIFTH INPUT) FROM MODEL

In order to absorption of sulfur in coke, limestone is used; therefore the amount of input limestone should be proportional to coke. Proper ratio of coke to the limestone is 10 to 1. Hence, the system would have four individual inputs; therefore they can be merged together due to the dependence on each other. Since, the main input to system is coal, limestone is merging into coal. Now removing the column 6 of main transfer function which connected to disturbance and merging column five, which connected to limestone into column three, a 4×4 transfer matrix is attained.

In order to achieve this aim, the main transfer function and state-space model of system shall be adjusted that has been illustrated bellow: The calculation method for adjusting transfer function while disturbance input is eliminated and merging is applied is the following way:

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} g_{11} & g_{12} & g_{13} & g_{14} & g_{15} \\ g_{21} & g_{22} & g_{23} & g_{24} & g_{25} \\ g_{31} & g_{32} & g_{33} & g_{34} & g_{35} \\ g_{41} & g_{42} & g_{43} & g_{44} & g_{45} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \end{bmatrix} = \begin{bmatrix} g_{11} & g_{12} & g_{13} & g_{14} & g_{15} \\ g_{21} & g_{22} & g_{23} & g_{24} & g_{25} \\ g_{31} & g_{32} & g_{33} & g_{34} & g_{35} \\ g_{41} & g_{42} & g_{43} & g_{44} & g_{45} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ 0.1\times u_5 \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} g_{11} & g_{12} & g_{13} & +0.1\times g_{15} & g_{14} \\ g_{21} & g_{22} & g_{23} & +0.1\times g_{25} & g_{24} \\ g_{31} & g_{32} & g_{33} & +0.1\times g_{35} & g_{34} \\ g_{41} & g_{42} & g_{43} & +0.1\times g_{45} & g_{44} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} \quad (7)$$

That is equivalent that state-space matrices can be reformed as follows:

$$A_{mod} = A \quad (8)$$

$$B_{mod} = \left[B(:,1), B(:,2), B(:,3)+0.1B(:,5), B(:,4)\right] \quad (9)$$

$$C_{mod} = C \quad (10)$$

$$D_{mod} = \left[D(:,1), D(:,2), D(:,3)+0.1D(:,5), D(:,4)\right] \quad (11)$$

Eliminating non-DIC pairings: In this study using five necessary condition of DIC, undesirable pairings has been eliminated.

Results of section two can be applied to decomposed the main transfer function to two split system. The first transfer function is a 4×4 system constructed by modification of plant without considering the input disturbance. In the second transfer function the effects of disturbance is considered. For a 4×4 system there are 24 possible pairings of inputs and outputs that the best pairing should be chosen. In the following, the five necessary conditions that is required to deduction that system is DIC is scrutinized.

Remark: To verify DIC necessary conditions a MATLAB function has been developed.

Eliminate Pairings with Negative RGA's[8]: Details of these removed pairing are exhibited in Table 1. Eliminated pairings are depicted in hatched cells.

Eliminate Pairings with Negative Niederlinski Indexes [8]:

$$NI = \frac{\det\left(G(0)\right)}{\prod_{i=1}^{n} g_{ii}} \quad (12)$$

The pairings that are eliminated applying this rule are shown in Table 1-9. Those pairings in 100% operating point that don't eliminate using the rule one and two together with Niederlinski Indexes coefficient are shown in Table 2. Furthermore, for the sake of concision, Niederlinski Index of Non-eliminating pairings at two other operating points do not tabulated.

Table 1: Eliminated pairings in three operating point using the first DIC criteria

Operating point	0(%)	50(%)	100(%)
Pairing	1	1	1
	2	2	2
	3	3	3
	4	4	4
	5	5	5
	6	6	6
	7	7	7
	8	8	8
	9	9	9
	10	10	10
	11	11	11
	12	12	12
	13	13	13
	14	14	14
	15	15	15
	16	16	16
	17	17	17
	18	18	18
	19	19	19
	20	20	20
	21	21	21
	22	22	22
	23	23	23
	24	24	24

Table 2: Niederlinski index of non-eliminating pairings at 100% operating point using rules one and two

Pairing	Niederlinski index
3	3.081
4	41.299
5	11.693
6	663.574
9	2.986
10	4.272
11	11.332
12	68.639
18	146.178

Eliminate pairings with negative morari indexes of integral controllability[8]:

$$MIC = Re\left\{\lambda\left(G^{+}(0)\right)\right\} \quad (13)$$

Applying this rule to 24 initial pairings at 100% operating point only seven pairings of them are remained. These pairings and MIC coefficient of them as well Niederlinski Indexes coefficients are shown in Table 3. Rule three is redundant to rule two that is, rule three always implies rule two as special case. As can be seen, those pairings that are eliminated in Table 4 are eliminated in Table 5 too.

Eliminate Pairing with Negative Introduced Index in the paper:

$$I = Re\left\{\lambda\left(G^{+}(0)*K_c\right)\right\} \quad (14)$$

Table 3: MIC and niederlinski index of non-eliminating pairings using third rule

Pairing	MIC	Niederlinski index
3	0.311273	3.081
4	0.098468	41.299
5	0.139686	11.693
9	0.423586	2.986
10	0.126011	4.272
11	0.14496	11.332
12	0.034565	68.639

Table 4: Eliminated pairings in three operating point using the second DIC criteria

Second rule		
0(%)	50(%)	100(%)
1	1	1
2	2	2
3	3	3
4	4	4
5	5	5
6	6	6
7	7	7
8	8	8
9	9	9
10	10	10
11	11	11
12	12	12
13	13	13
14	14	14
15	15	15
16	16	16
17	17	17
18	18	18
19	19	19
20	20	20
21	21	21
22	22	22
23	23	23
24	24	24

In Eq. 14, K_c is diagonal Matrix with positive random entries between zero to one[8]. The equation is originated by DIC properties. If a system and a particular pairing is DIC, The bellow condition must be satisfied:

$$\text{DIC}: \forall C \rightarrow \lambda\left(G^{+}(0)C(0)\right) > 0 \tag{15}$$

In this study, it is suggested to use C(0) as random numerical positive diagonal matrix for eliminating non-DIC pairing. So, if for the supposed matrix C(0) the (15) is not satisfied, the selected pairing is not DIC. Because, in this formula the controller is randomly selected, thus presumably some of remained pairings may be eliminated despite the previous rules had accepted them.

Finally, those pairings that aren't eliminated are three, four and five. Because Bed mass variable would not be controlled by Char variable, these pairings is unsuitable. As noticed at Table 1 and 5, only the pairings 1 and 3 satisfied the DIC criteria at two operating points.

Table 5: Eliminated pairings in three operating point using the third DIC criteria

Third rule		
0(%)	50(%)	100(%)
1	1	1
2	2	2
3	3	3
4	4	4
5	5	5
6	6	6
7	7	7
8	8	8
9	9	9
10	10	10
11	11	11
12	12	12
13	13	13
14	14	14
15	15	15
16	16	16
17	17	17
18	18	18
19	19	19
20	20	20
21	21	21
22	22	22
23	23	23
24	24	24

Table 6: Verisimilar pairings while char input and bed mass output are removed

-	Air	Coal	Steam	-	Air	Coal	Steam
CV	1	0	1	CV	1	0	1
P	0	1	0	P	0	1	0
T	0	0	1	T	0	0	1
CV	0	1	0	CV	0	0	1
P	0	0	1	P	0	1	0
T	1	0	0	T	1	0	0
CV	0	1	0	CV	1	0	1
P	1	0	0	P	1	0	1
T	0	0	1	T	0	1	0

Selecting suitable pairing: In the previous section, using necessary conditions of DIC, some pairings that are not DIC was eliminated. In this study using the chemical laws, RGA and interaction measure, suitable pairing is attained between remained pairings.

Eliminating non practical pairing with regard to criterion of chemical law: In sight of governing law of Gasifier, Bed mass should be controlled by Char value, therefore only six of 24 pairings remain which is shown in Table 6.

In Table 7, priority of which inputs that is appropriate to control of certain output is depicted. Basic of concluding of Table 6 is [13-17]. Pairing 9 and 10 satisfies the criteria of Table 16, therefore since the pairing 10 is DIC, it proposed as appropriate pairing.

Eliminating non practical pairing with regard to criterion of RGA: RGA is one of the common criterion

Table 7: Quantitative comparing of influence of inputs to outputs

Control variable	Maximum influence	Moderate influence	Minimum influence
CV	Air, Steam, Coal		
P	Air	Steam	Coal
T	Air, Steam, Coal		

Table 8: RGA matrix of pairing 10 at three operating point

	RGA matrix of pairing number 10			
Percentage	1	2	3	4
100%	0.24043	0.41325	-0.07243	0.41874
	0.02745	0.57812	-0.03016	0.42459
	0.02651	0.01499	0.90664	0.05186
	0.70561	-0.00636	0.19595	0.10481
50%	0.34549	0.70517	-0.03487	-0.0158
	0.03490	0.30983	-0.04576	0.70102
	0.03935	0.03203	0.89067	0.03796
	0.58026	-0.04703	0.18996	0.27682
0%	0.45544	2.48034	0.03949	-1.97527
	0.08283	-1.10107	-0.14712	2.16536
	0.07419	0.08885	0.89224	-0.05528
	0.38754	-0.46811	0.21538	0.86520

Table 9: RGA Matrix of pairing 12 at three operating point

	RGA matrix of pairing number 10			
Percentage	1	2	3	4
100	0.24043	0.41325	0.41874	-0.07243
	0.02745	0.57812	0.42459	-0.03016
	0.02651	0.01499	0.05186	0.90664
	0.70561	-0.00636	0.10481	0.19595
50	0.34549	0.70517	-0.0158	-0.03487
	0.03490	0.30983	0.70102	-0.04576
	0.03935	0.03203	0.03796	0.89067
	0.58026	-0.04703	0.27682	0.18996
0	0.45544	2.48034	-1.97527	0.03949
	0.08283	-1.10107	2.16536	-0.14712
	0.07419	0.08885	-0.05528	0.89224
	0.38754	-0.46811	0.86516	0.21538

for choosing appropriate pairing in steady state. Based on this criterion, suitable pairing most have following properties[17, 18].

- Diagonal entries of matrix must be positive
- Diagonal entries of matrix should be close to one
- Diagonal entries of matrix shouldn't be a large number
- RGA matrices of pairings 10 and 12 at three operating point 0, 50 and 100% is depicted in Table 8

As seen from Table 8 , entries (1, 1) and (2, 2) at all operating points are equal. Only difference between these matrixes is in entries (3, 3) and (4, 4). At all operating points pairing 10 is preferred to other pairings.

Eliminating non practical pairing with regard to interaction criterion: Checking the interaction value of pairing is the one of the best benchmark to choosing suitable one. To determine the interaction value for each pairing, Column Dominance Ratio (CDR) value is used[19, 20].

Table 10: Interaction comparison of pairings 10 and 12 via three method in three operating points

Percentage	Pairing	First method	Second method	Third method
100	10	0.591033	34.68118	13489104
		292.0804	19412.6	
		13.35201	627.981	
		248903.5	13469029	
	12	0.591033	34.68118	15606966
		292.0804	19412.6	
		29.45819	1043.81	
		261249.6	15586475	
50	10	0.40804	15.81136	12673927
		373.783	26410.41	
		28.0286	1553.429	
		190975.4	12645948	
	12	0.40804	15.81136	20939833
		373.783	26410.41	
		81.8810	2852.286	
		318917.8	20910555	
0	10	0.025173	1.016867	8591486
		575.1852	55194.49	
		122.2918	10705.82	
		201465.9	8525585	
	12	0.025173	1.016867	15129989
		575.1852	55194.49	
		341.1147	22648.63	
		408657.0	15052145	

Now, there are three procedures to determine the interaction value. In the first method, maximum value of CDR of each loops are selected as the assessment of interaction. Second method, is the summation of CDR of each loop in adequate points that are in range between steady state to 10 times of bandwidth. Third method is summation of second method in all loops. Table 9 is allocated to comparison of interaction between pairing 10 and 12. As seen in Table 10, pairing 10 is more appropriate than pairing 12.

CONCLUSION

To choose an appropriate pairing, it is attempted to find a pairing that is DIC, minimal interaction and compatible with chemical laws. At first by exerting the necessary criteria of DIC, those only pairings that would not eliminated at three operating points are three, four and five. As noted in the text of paper, in sight of practical implementation, these pairings are not suitable ones. Consequently, there is no pairing which satisfies the necessary criteria of DIC at all operating points. Inasmuch

50 and 100% operating points are prominent to 0, operating point, those pairings that satisfies the necessary criteria of DIC at these operating points are picked out as appropriate pairings. Only pairings that satisfies necessary criteria of DIC at 50 and 100% operating points are 10 and 12.

In sight of introduced procedure for interaction quantifying, tenth pairing is suitable than twelfth. Also, in terms of chemical law, relations between inputs and outputs in pairing 10 are more conceivable than twelfth. Finally, pairing 10 is suggested for decentralized controller.

Appendix; corresponding pairings to number:

$$1\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}\quad 9\begin{bmatrix}0&0&1&0\\1&0&0&0\\0&1&0&0\\0&0&0&1\end{bmatrix}\quad 17\begin{bmatrix}0&0&1&0\\0&0&0&1\\1&0&0&0\\0&1&0&0\end{bmatrix}$$

$$2\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\end{bmatrix}\quad 10\begin{bmatrix}0&0&0&1\\1&0&0&0\\0&1&0&0\\0&0&1&0\end{bmatrix}\quad 18\begin{bmatrix}0&0&0&1\\0&0&1&0\\1&0&0&0\\0&1&0&0\end{bmatrix}$$

$$3\begin{bmatrix}1&0&0&0\\0&0&1&0\\0&1&0&0\\0&0&0&1\end{bmatrix}\quad 11\begin{bmatrix}0&0&1&0\\1&0&0&0\\0&0&0&1\\0&1&0&0\end{bmatrix}\quad 19\begin{bmatrix}0&1&0&0\\0&0&1&0\\0&0&0&1\\1&0&0&0\end{bmatrix}$$

$$4\begin{bmatrix}1&0&0&0\\0&0&0&1\\0&1&0&0\\0&0&1&0\end{bmatrix}\quad 12\begin{bmatrix}0&0&0&1\\1&0&0&0\\0&0&1&0\\0&1&0&0\end{bmatrix}\quad 20\begin{bmatrix}0&1&0&0\\0&0&0&1\\0&0&1&0\\1&0&0&0\end{bmatrix}$$

$$5\begin{bmatrix}1&0&0&0\\0&0&1&0\\0&0&0&1\\0&1&0&0\end{bmatrix}\quad 13\begin{bmatrix}0&1&0&0\\0&0&1&0\\1&0&0&0\\0&0&0&1\end{bmatrix}\quad 21\begin{bmatrix}0&0&1&0\\0&1&0&0\\0&0&0&1\\1&0&0&0\end{bmatrix}$$

$$6\begin{bmatrix}1&0&0&0\\0&0&0&1\\0&0&1&0\\0&1&0&0\end{bmatrix}\quad 14\begin{bmatrix}0&1&0&0\\0&0&0&1\\1&0&0&0\\0&0&1&0\end{bmatrix}\quad 22\begin{bmatrix}0&0&0&1\\0&1&0&0\\0&0&1&0\\1&0&0&0\end{bmatrix}$$

$$7\begin{bmatrix}0&1&0&0\\1&0&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}\quad 15\begin{bmatrix}0&0&1&0\\0&1&0&0\\1&0&0&0\\0&0&0&1\end{bmatrix}\quad 23\begin{bmatrix}0&0&1&0\\0&0&0&1\\0&1&0&0\\1&0&0&0\end{bmatrix}$$

$$8\begin{bmatrix}0&1&0&0\\1&0&0&0\\0&0&0&1\\0&0&1&0\end{bmatrix}\quad 16\begin{bmatrix}0&0&0&1\\0&1&0&0\\1&0&0&0\\0&0&1&0\end{bmatrix}\quad 24\begin{bmatrix}0&0&0&1\\0&0&1&0\\0&1&0&0\\1&0&0&0\end{bmatrix}$$

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