CONTROL STRUCTURE SELECTION FOR THE ALSTOM GASIFIER BENCHMARK PROCESS USING GRDG ANALYSIS

Rudy Agustriyanto[1,2], Jie Zhang[1]

[1]School of Chemical Engineering and Advanced Materials, University of Newcastle, Newcastle upon Tyne NE1 7RU, UK
[2]University of Surabaya, Indonesia

Abstract: The objective of this work is to explore the disturbance rejection capability of possible multi-loop control structures for the ALSTOM gasifier benchmark process and selecting the appropriate control structure. Generalized Relative Disturbance Gain (GRDG) analysis is used for control structure determination. In order to carry out GRDG analysis, process models in the form of transfer functions are obtained from the discrete time models identified using the Output-Error (OE) method for system identification. Models identified with the OE method can provide accurate long range prediction (or simulation) performance and, hence, lead to accurate transfer function models. The GRDG analysis results clearly show that the baseline controller proposed by Asmar et al. (Asmar et al., 2000) is the favoured multi-loop control structure among their initial designs. This study provides explanation for the reason behind the impressive performance of the ALSTOM baseline controller that is not available before.

Keywords: ALSTOM Gasifier, Relative Disturbance Gain Array, Plantwide Control, Process Control.

1. INTRODUCTION

In 1997 the ALSTOM Power Technology Centre issued an open challenge to the UK academic control community, which addressed the control of a Gasifier plant (Dixon et al., 2000). The ‘challenge information pack’ included three linear models (obtained from ALSTOM’s comprehensive non-linear model of the system). Full detail of this challenge can be found in reference (Burnham et al., 2000; Dixon et al., 2000).

Among the approaches that have been proposed to solve this challenging problem, Asmar et al. (Asmar et al., 2000) provide a relatively simple controller structure but with excellent control performance. It only fails in its regulation task during one of the six pressure disturbance tests. Later this structure was adopted and used as a baseline controller in the second round of ALSTOM benchmark challenge (Dixon and Pike, 2004), where the nonlinear simulation programme for the process is provided. Unfortunately, up to now there have been no formal analysis on why the baseline control structure gives good performance and no theoretical analysis in a systematic manner have been given to explain the evolution from the initial design towards the final solution (baseline controller).

Some other more complex control approaches proposed for this benchmark process include multi-objective optimization (Griffin et al., 2000) and multivariable proportional-integral (PI) controller tuning methodology based on multi-objective optimization (Liu et al., 2000). Taylor et al. (Taylor et al., 2000) proposed multivariable proportional-integral plus (PIP) controllers. Rice et al. (2000) used model predictive control to control this process. A sequential loop selection technique combined with high frequency decoupling is applied to the benchmark process (Munro et al., 2000).

This paper is organized as follows. Section 2 gives an overview of the GRDG method. Section 3 presents model identification of the ALSTOM gasifier using simulated process operation data from the nonlinear simulation programme. Section 4 provides GRDG analysis for control structure determination. The paper ends with some conclusions.

2. GENERALIZED RELATIVE DISTURBANCE GAIN (GRDG)

Based on the process and disturbance transfer functions, Stanley et al. (Stanley et al., 1985) proposed the relative disturbance gain (RDG) for analysing the disturbance rejection capability in multi-loop control. The RDG overcomes one of the limitations of the RGA (relative gain array) by allowing disturbances to be included in an operability analysis.

For the following multivariable process:

$$y = G.u + G_d .d \tag{1}$$

where y is the output, u is the manipulated variable and d is the disturbance. The ith element of RDG is defined as (Stanley et al., 1985) :

$$\beta_i = \frac{\left[\dfrac{\partial u_i}{\partial d}\right]_{y_j}}{\left[\dfrac{\partial u_i}{\partial d}\right]_{yi,uij\neq}} \tag{2}$$

The term in the numerator denotes the change in the manipulated variable u_i needed for perfect disturbance rejection. The term in the denominator represents the change in manipulated variable u_i when one of the output y_i is kept perfect. Equation (2) can be rearranged and the vector of RDG can be expressed as:

$$RDG\{G, G_{diag}, Gd\} = \left(G^{-1}G_d\right) \varnothing \left(\left(G_{diag}\right)^{-1}G_d\right) \tag{3}$$

where $\varnothing$denotes element by element division.

The concept of RDGA is very similar to RGA (Bristol, 1966) except that RDGA emphases on load disturbance rejection. Since RDG is pairing dependent (β_i depends on the input-output pairing), an $n\times n$ array can be constructed after going through n possible pairings (forming n vectors). Therefore, an augmented version of relative disturbance gain β_{ij} can be defined and a matrix can be formed. The matrix RDGA (B) is defined as (Chang and Yu, 1992):

$$\mathrm{B} = \begin{array}{cc} & \begin{matrix} u_1 & u_2 & \cdots & u_n \end{matrix} \\ & \begin{bmatrix} \beta_{11} & \beta_{12} & \cdots & \beta_{1n} \\ \beta_{21} & \beta_{22} & & \beta_{2n} \\ . & \cdots & & . \\ \beta_{n1} & \cdots & \cdots & \beta_{nn} \end{bmatrix} \begin{matrix} y_1 \\ y_2 \\ . \\ y_n \end{matrix} \end{array} \tag{4}$$

The ijth entry, β_{ij}, corresponds to the RDG when the ith output is paired with the jth input. Notice that, since the vector G_d is involved in the computation of β_{ij}, corresponding changes in G_d have to be made in permutation in the outputs in the matrix G.

In a matrix notation, the B matrix can be promptly calculated from:

$$B = \left[G^{-1}.diag(Gd)\right]^{-1}.\left[diag\left(G^{-1}G_d\right)\right] \tag{5}$$

where diag(.) transforms a vector (.) into a matrix with elements put on the corresponding diagonal positions, that is, the ith element of a vector (.) is put in the iith entry of a matrix. Equation (5) simplifies the computation of RDGA.

An interaction measure GRDG is defined to evaluate the load effect under a specific controller structure (closed-loop load effect) over the open loop load effect (Chang and Yu, 1992):

$$\text{GRDG} = \frac{\text{closed-loop load effect}}{\text{Open-loop load effect}} \tag{6}$$

GRDG is a vector which is a function of $G, \tilde{G}$ and G_d. Mathematically it becomes:

$$\begin{aligned} GRDG &= \{G, \tilde{G}, G_d\} = G_d^{\,*} \varnothing\ G_d \\ &= \left(\tilde{G}.G^{-1}.G_d\right) \varnothing G_d \end{aligned} \tag{7}$$

where $\tilde{G}$ is the process model in IMC for defining the controller structure (detail can be found in (Chang and Yu, 1992)).

GRDG is a vector with element $\delta_i = g_{d,i}^{\,*} / g_{d,i}$ where $g_{d,i}^{\,*}$ is the ith element of $G_d^{\,*}$ and $g_{d,i}$ is the ith element of G_d. Physically, GRDG measures the net load effect of a specific controller structure over the open loop load effect. The controller structure can take any form of interest except for the ratio schemes.

In order to characterize the controller structure, a structure election matrix, Γ, is defined as:

$$\Gamma = \begin{bmatrix} \gamma_{11} & \gamma_{12} & \cdots & \gamma_{1n} \\ \gamma_{21} & \gamma_{22} & \cdots & \gamma_{2n} \\ . & \cdots & \cdots & . \\ \gamma_{n1} & \cdots & \cdots & \gamma_{nn} \end{bmatrix} \tag{8}$$

where the ijth entry γ_{ij} is defined as:

γ_{ij} =1, element picked up (for the controller structure)

γ_{ij} =0, element ignored

If the structure of $\tilde{G}$ is specified, the GRDG for the ith output of δ_i is simply the row wise summation of RDGA with corresponding structure. Mathematically:

$$\delta_i = \sum_{j=1}^{n} \beta_{i,j}\gamma_{ij} \tag{9}$$

3. PROCESS MODEL IDENTIFICATION

The ALSTOM gasifier benchmark problem as shown in Figure 1, has five inputs (coal, limestone, air, steam and char extraction) and four outputs (pressure, temperature, bed mass and gas quality). In addition, there is a disturbance input, PSINK, representing pressure disturbances induced as the gas turbine fuel inlet valve is opened and closed.

Although a linearised state space model is available for the ALSTOM benchmark process, here linear models are identified from the simulated process operation data using the nonlinear simulation programme. This is because that, in practical applications, process models are generally not available and have to be identified from process operation data.

Step tests were performed for input and disturbance variables. The complete transfer function expected is in the form:

$$\begin{bmatrix} y1 \\ y2 \\ y3 \\ y4 \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} & G_{13} & G_{14} & G_{15} \\ G_{21} & G_{22} & G_{23} & G_{24} & G_{25} \\ G_{31} & G_{32} & G_{33} & G_{34} & G_{35} \\ G_{41} & G_{42} & G_{43} & G_{44} & G_{45} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \end{bmatrix} + \begin{bmatrix} G_{d1} \\ G_{d2} \\ G_{d3} \\ G_{d4} \end{bmatrix} .d$$

where:
y1 = CVGAS = fuel gas caloric value (J/kg)
y2 = MASS = bed mass (kg)
y3 = PGAS = fuel gas pressure (N/m2)
y4 = TGAS = fuel gas temperature (K)

u1 = WCHR = char extraction flow (kg/s)
u2 = WAIR = air mass flow (kg/s)
u3 = WCOL= coal flow (kg/s)
u4 = WSTM= steam mass flow (kg/s)
u5 = WLS = limestone mass flow (kg/s)

d = PSINK = sink pressure (N/m2)

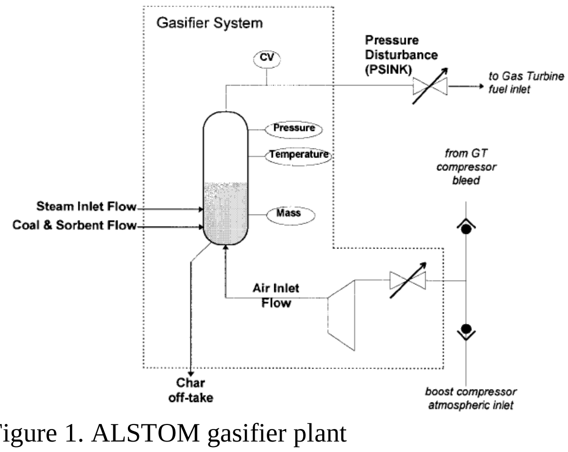

Figure 1. ALSTOM gasifier plant

The Output Error (OE) method is used to identify the process model of the following form:

$$y(t) = \frac{B(q)}{F(q)} u(t - n_k) + e(t)$$

Second order models are identified and are then converted into continuous time transfer functions. The OE method is used because it can lead to models with good long range prediction (or simulation) performance and, hence, accurate transfer function models.

For step tests in char flow (u1) as shown in Figure 2, the numerators and denominators of the transfer functions are summarized in Table 2. Plots of actual responses and the simulated values using the identified models are shown in Figure 3. It can be seen that the models are satisfactory.

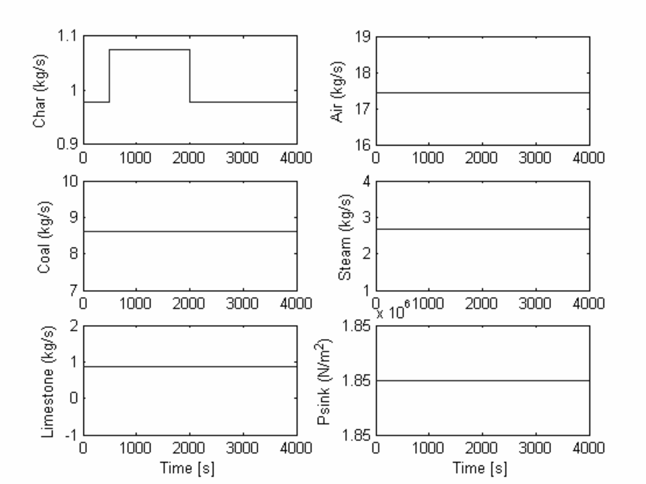

Figure 2. Profile of input and disturbance variables for step up and down of char flow (u1).

Table 2. Identified models

	y(t) = [B(q)/F(q)]u(t) + e(t)	Transfer Function
y1	$B(q) = 288.4\ q^{-1} - 288.3\ q^{-2}$ $F(q) = 1-1.999\ q^{-1} + 0.9991\ q^{-2}$	$\frac{288.5\ s + 0.1317}{s^2 + 0.0009365\ s + 6.404e\text{-}7}$
y2	$B(q) = -1.083\ q^{-1} + 1.082\ q^{-2}$ $F(q) = 1 - 1.999\ q^{-1} + 0.9992\ q^{-2}$	$\frac{-1.083\ s - 0.001157}{s^2 + 0.0007612\ s + 2.081e\text{-}7}$
y3	$B(q) = 10.88\ q^{-1} - 10.88\ q^{-2}$ $F(q) = 1 - 1.999\ q^{-1} + 0.9994\ q^{-2}$	$\frac{10.88\ s - 0.001442}{s^2 + 0.0006466\ s + 6.668e\text{-}8}$
y4	$B(q) = 0.06391\ q^{-1} - 0.0639\ q^{-2}$ $F(q) = 1 - 1.999\ q^{-1} + 0.9992\ q^{-2}$	$\frac{0.06393\ s + 9.769e\text{-}006}{s^2 + 0.0007962\ s + 3.623e\text{-}7}$

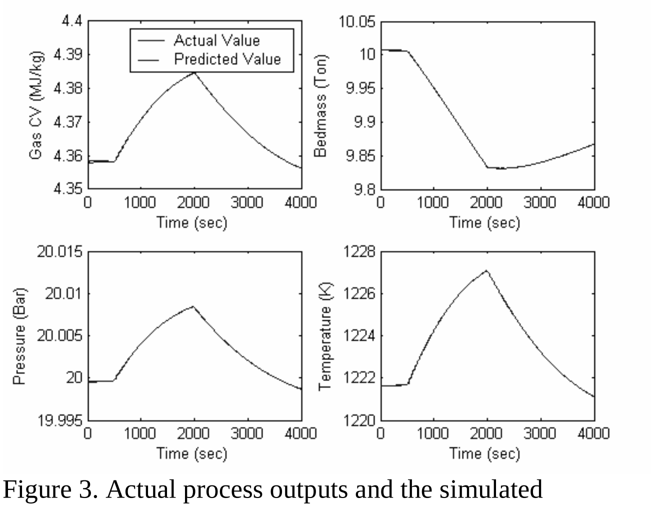

Figure 3. Actual process outputs and the simulated values from the identified linear model

The same method is applied for the rest of variables and the final results of transfer functions are presented in Table 3. The magnitude of step tests are

+ 10% and -10% of the corresponding steady state values of the manipulated variables at times 500 s and 2000 s. For pressure disturbance test, step up and down values are ± 0.2 bar.

Table 3. Identified transfer functions

G	Transfer Function
G11	$\frac{288.5 s + 0.1317}{s^2 + 0.0009365 s + 6.404e-7}$
G21	$\frac{-1.083 s - 0.001157}{s^2 + 0.0007612 s + 2.081e-7}$
G31	$\frac{10.88 s - 0.001442}{s^2 + 0.0006466 s + 6.668e-8}$
G41	$\frac{0.06393 s + 9.769e-006}{s^2 + 0.0007962 s + 3.623e-7}$
G12	$\frac{-6927 s +1.95}{s^2 + 0.04927 s + 6.26 e-5}$
G22	$\frac{-0.428 s + 0.000201}{s^2 – 0.0003426 s – 3.039 e -8}$
G32	$\frac{2444 s + 6.167}{s^2 + 0.2465 s + 0.0003653}$
G42	$\frac{0.04664 s + 1.779 e-5}{s^2 + 0.001197 s + 5.86 e-7}$
G13	$\frac{5303 s – 6.382}{s^2 + 0.03363 s + 4.306 e-5}$
G23	$\frac{0.5327 s + 0.001158}{s^2 + 0.001245 s + 2.746 e-7}$
G33	$\frac{1039 s – 1.618}{s^2 + 0.2468 s + 0.0003226}$
G43	$\frac{-0.05418 s + 1.318 e-5}{s^2 + 0.0005866 s – 9.745 e-8}$
G14	$\frac{5035 s – 1.029}{s^2 + 0.02632 s + 8.23 e-6}$
G24	$\frac{-0.7753 s – 0.004223}{s^2 + 0.007574 s + 5.086 e-6}$
G34	$\frac{4800 s + 0.4871}{s^2 + 0.3032 s + 9.41 e-5}$
G44	$\frac{-0.005225 s – 4.671 e-5}{s^2 + 0.00226 s + 9.812 e-7}$
G15	$\frac{-183.3 s + 0.05493}{s^2 + 0.0003089 s – 1.073 e-7}$
G25	$\frac{0.219 s + 0.0009288}{s^2 + 0.001592 s + 3.119 e-7}$
G35	$\frac{439.6 s – 0.2743}{s^2 + 0.0958 s + 8.924 e-5}$
G45	$\frac{-0.02776 s – 4.475 e-5}{s^2 + 0.001509 s + 1.233 e-6}$
Gd1	$\frac{0.02226 s – 2.345 e-6}{s^2 + 0.06283 s + 0.0001897}$
Gd2	$\frac{1.764 e-6 s -1.04 e-9}{s^2 + 6.625 e-5 s – 3.419 e-7}$
Gd3	$\frac{0.3813 s + 0.001229}{s^2 + 0.411 s + 0.001331}$
Gd4	$\frac{-1.237 e-7 + 9.687 e-12}{s^2 + 0.001347 s + 4.068 e-7}$

The process model identification here is based on the simulated process operation data at 100% load case and will be used for control operability analysis of control structures given in Asmar et al. (2000), which are also based solely on 100% load.

4. GRDG ANALYSIS FOR THE ALSTOM GASIFIER

The steady state gain matrix (based on the identified transfer functions) for the ALSTOM gasifier is presented below:

$$G(0)=\begin{bmatrix} 2.0565e5 & 3.1150e4 & -1.4821e5 & -1.2503e5 & -5.1193e5 \\ -5.5598e3 & -6.6140e3 & 4.2170e3 & -830.3185 & 2.9779e3 \\ -2.1626e4 & 1.6882e4 & -5.0155e3 & 5.1764e3 & -3.0737e3 \\ 26.9638 & 30.3584 & -135.2488 & -47.6050 & -36.2936 \end{bmatrix}$$

From the above steady state gain matrix, the 5th column is deleted since u5 is set to 10% of u3 in closed loop system. This left 4 degree of freedom and the matrix is now square matrix.

$$G(0)=\begin{bmatrix} 2.0565e5 & 3.1150e4 & -1.4821e5 & -1.2503e5 \\ -5.5598e3 & -6.6140e3 & 4.2170e3 & -830.3185 \\ -2.1626e4 & 1.6882e4 & -5.0155e3 & 5.1764e3 \\ 26.9638 & 30.3584 & -135.2488 & -47.6050 \end{bmatrix}$$

Based on Table 3, the steady state vector disturbance can also be calculated:

$$Gd(0)=\begin{bmatrix} -0.0124 \\ 0.0030 \\ 0.9234 \\ 2.3813e-5 \end{bmatrix}$$

RDGA matrix is calculated by using Equation (5):

$$\beta=\begin{bmatrix} 448.4189 & -122.8589 & 343.3579 & -667.9180 \\ 50.1089 & -107.8234 & 40.3807 & 18.3339 \\ 0.6332 & 0.8941 & -0.1560 & -0.3713 \\ -30.6157 & 62.3498 & -163.1588 & 132.4247 \end{bmatrix}$$

For comparison purposes, the GRDG of the four schemes presented in (Asmar et al., 2000) will be calculated.

Scheme 1: (y1-u3) (y2 – u1) (y3 – u2) (y4-u4)

$$\Gamma_1 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$GRDG_1 = [343.3579 \quad 50.1089 \quad 0.8941 \quad 132.4247]^T$$

Scheme 2: (y1–u3) (y2-u1) (y3-u4) (y4-u2)

$$\Gamma_2 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$GRDG_2 = [343.3579 \quad 50.1089 \quad -0.3713 \quad 62.3498]^T$$

Scheme 3: (y1–u2) (y2-u3) (y3-u4) (y4-u1)

$$\Gamma_3 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

$$GRDG_3 = [-122.8589 \quad 40.3807 \quad -0.3713 \quad -30.6157]^T$$

Scheme 4: (y1–u2) (y2-u3,u1) (y3-u4) (y4-u1)

$$\Gamma_4 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

$$GRDG_4 = [-122.8589 \quad -9.7282 \quad -0.3713 \quad -30.6157]^T$$

From the IE (integral error) standpoint, a structure giving small value in δ_i is preferred (Chang and Yu, 1992). It is obvious that Scheme 4 is the most favourable pairing among the 4 schemes. It can also be concluded from these GRDG values that Scheme 2 would be better than Scheme 1 and Scheme 3 would be better than Scheme 2 in terms of disturbance rejection performance. Simulation results in (Asmar et al., 2000) and (Dixon and Pike, 2004) confirmed these.

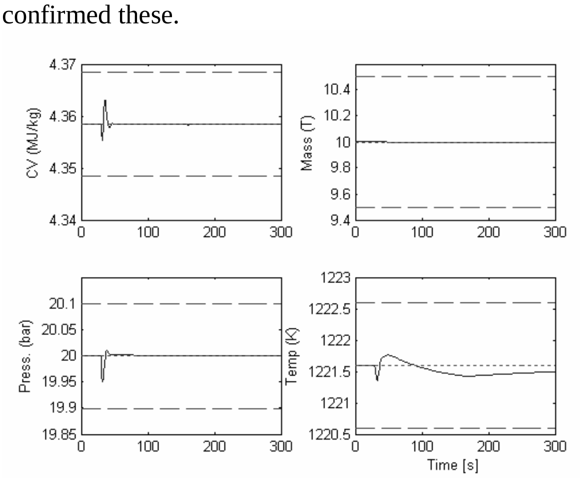

Figure 4. Process response to step pressure disturbance at 100% load

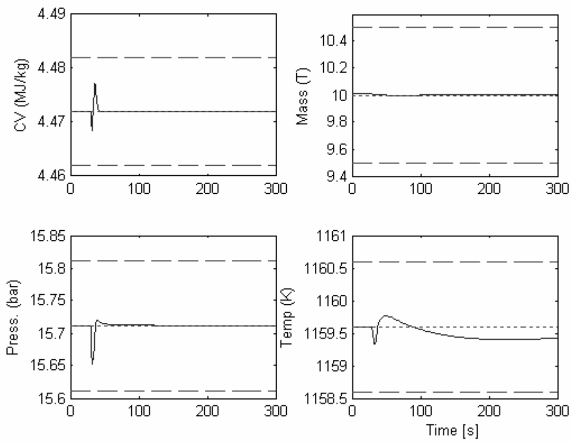

Figure 5. Process response to step pressure disturbance at 50% load

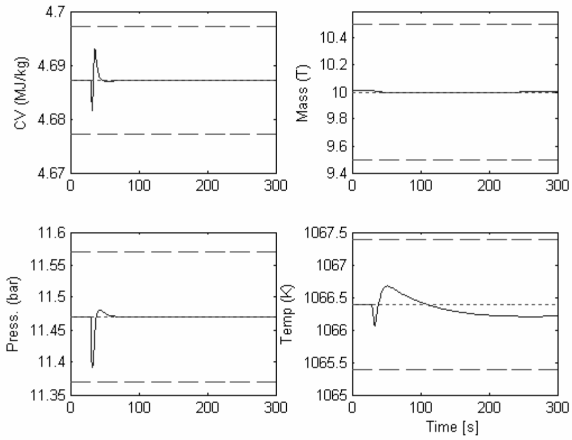

Figure 6. Process response to step pressure disturbance at 0% load

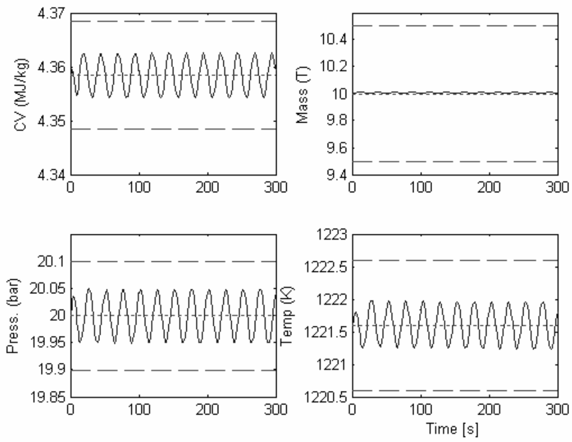

Figure 7. Process response to sinusoidal pressure disturbance at 100% load

Figures 4 to 8 show the control performance of Scheme 4. As can be seen from Figures 4 to 8, the controlled variables under Scheme 4 do not exceed their constraints during step disturbance tests at all three operating load and sinusoidal disturbance tests at 100% and 50% operating load.

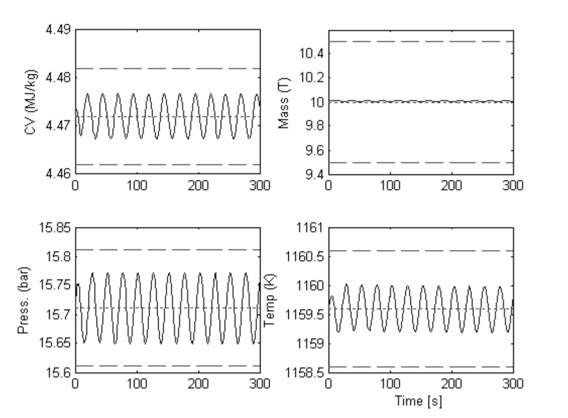

Figure 8. Process response to sinusoidal pressure disturbance at 50% load

5. CONCLUSIONS

A systematic method for assessing the disturbance rejection performance of different control structures for the ALSTOM gasifier using GRDG is presented in this paper. The analysis is based on the transfer function model identified from the simulated process operation data based on the nonlinear simulation programme. The OE method is used in identifying process models because it can lead to models with good long range prediction (simulation) performance and, hence, accurate transfer function models. It is shown that Scheme 4 is the most favoured control structure among the 4 control structures considered. Simulation results confirm this finding. Studies in this paper also indicate that using RGA analysis is not effective in control structure selection for this benchmark process. It would be possible to find even better control structures using GRDG analysis and this is under further investigation.

ACKNOWLEDGMENT

This work was supported by Technological and Professional Skills Development Sector Project (TPSDP) – ADB Loan No.1792 – INO. This support is gratefully acknowledged.

REFERENCES

Asmar, B. N., Jones, W. E., and Wilson, J. A. (2000). A process engineering approach to the ALSTOM gasifier problem. *Proceedings of the Institution of Mechanical Engineers Part I-Journal of Systems and Control Engineering*, **v. 214, no. 16**, p. 441-452.

Bristol, E. (1966). On a new measure of interaction for multivariable process control. *IEEE Transaction on Automaatic Control*, **v. 11, no. 1**, p. 133-134.

Burnham, K., Young, P., and Dixon, R. (2000). Special issue on the ALSTOM gasifier control engineering benchmark challenge. *Proceedings of the Institution of Mechanical Engineers Part I-Journal of Systems and Control Engineering*, **v. 214, no. 16,** p. I-II.

Chang, J. W., and Yu, C. C. (1992). Relative Disturbance Gain Array. *Aiche Journal*, **v. 38, no. 4,** p. 521-534.

Dixon, R., and Pike, A. W. (2004). Introduction to the 2nd ALSTOM benchmark challenge on gasifier control, *in Control 2004*, Bath, UK.

Dixon, R., Pike, A. W., and Donne, M. S. (2000). The ALSTOM benchmark challenge on gasifier control. *Proceedings of the Institution of Mechanical Engineers Part I-Journal of Systems and Control Engineering*, **v. 214, no. 16**, p. 389-394.

Griffin, I. A., Schroder, P., Chipperfield, A. J., and Fleming, P. J. (2000). Multi-objective optimization approach to the ALSTOM gasifier problem. *Proceedings of the Institution of Mechanical Engineers Part I-Journal of Systems and Control Engineering*, **v. 214, no. 16**, p. 453-468.

Liu, G. P., Dixon, R., and Daley, S. (2000). Multi-objective optimal-tuning proportional-integral controller design for the ALSTOM gasifier problem. *Proceedings of the Institution of Mechanical Engineers Part I-Journal of Systems and Control Engineering*, **v. 214, no. 16**, p. 395-404.

Munro, N., Edmunds, J. M., Kontogiannis, E., and Impram, S. T. (2000). A sequential loop closing approach to the ALSTOM gasifies problem. *Proceedings of the Institution of Mechanical Engineers Part I-Journal of Systems and Control Engineering*, **v. 214, no. 16**, p. 427-439.

Rice, M. J., Rossiter, J. A., and Schuurmans, J. (2000). An advanced predictive control approach to the ALSTOM gasifier problem. *Proceedings of the Institution of Mechanical Engineers Part I-Journal of Systems and Control Engineering*, **v. 214, no. 16**, p. 405-413.

Stanley, G., Marinogalarraga, M., and McAvoy, T. J. (1985). Shortcut Operability Analysis .1. The Relative Disturbance Gain. *Industrial & Engineering Chemistry Process Design and Development*, **v. 24, no. 4**, p. 1181-1188.

Taylor, C. J., McCabe, A. P., Young, P. C., and Chotai, A. (2000). Proportional-integral-plus (PIP) control of the ALSTOM gasifier problem. *Proceedings of the Institution of Mechanical Engineers Part I-Journal of Systems and Control Engineering*, **v. 214**, **no. 16**, p. 469-480.