Comparative Performance Evaluation of Model Reduction Techniques for a complex Non-Linear System

Anitha Mary.X[#1], L.Sivakumar[*2], J.Jayakumar[#3]

[#]Department of Electronics and Instrumentation Engineering *Dean
[#]Karunya University, Coimbatore, India.
* Sri Krishna College of Engineering and Technology, Coimbatore, India.
[1] anithamary@karunya.edu
[2] lingappansivakumar@gmail.com
[3]jayakumar@karunya.edu

***Abstract*: Many researchers showed their interest in solving the two challenge problems posed on academic community on controlling the gasifier by ALSTOM. Earlier part of the researchers tried advanced controller methods using the higher order state space model provided by ALSTOM. But, the inability to meet some constraints during integrated model and controller simulation, the authors have desired lower order MIMO transfer function models for the gasifier. Accordingly three lower order model representations for original higher order gasifier came to surface. However lower order model derived based on balanced realisation using Hankel singularity values method has only been successful in controlling gasifier for different types of disturbances and simultaneously meeting the input/output constraints. In this paper the authors investigate why all lower order model representation could not become successful sans balanced realisation method.**

Key words: ALSTOM gasifier, lower order modelling and simulation, balanced realisation using Hankel singularity values, auxiliary method, algebraic method.

I. INTRODUCTION

ALSTOM Gasifier is a complicated non linear process. Air, coal and steam are mixed to produce environmentally clean gas called syngas [1]. The outputs are pressure, temperature and calorific value of the syngas [2]. Two challenge problems have been posed by Alstom so as to provide a control philosophy which will ensure required gasifier performance requirements during disturbances emanating from load side as well as variations in calorific value of the coal from input side. Towards this, broadly three approaches have been found in the literature to evaluate the gasifier performance :

- Consider the higher order state space model as given by Alstom and try to tune the base line PI control algorithm. [7,8,9-22]
- Consider the higher order state space model as given by Alstom but try modern control algorithms such as model predictive control[3,21], H control [4], Sequential loop closing approach[6] and state estimation approach[5] , multi variable proportional integral plus control[11], partially decentralised control[23], self-adaptive differential evolution algorithm[18], active disturbance rejection control[24] , Non dominated sorting genetic algorithm II[15], Multi objective genetic algorithm[16] etc. for performance evaluation.
- Reduce the higher order state space model given by Alstom into low order transfer function models and try to tune the PI control algorithm[26-31]

In this paper, the authors investigate the accuracy and suitability of low order models derived by three distinct methods viz. balanced realisation using Hankel singularity values, auxiliary method and algebraic method.

II. PROBLEM STATEMENT:

Alstom gasifier system is having Air, coal, steam, lime stone and char as inputs and calorific value, pressure and temperature of syngas and bed mass as output variables. This constitutes a 5x4 MIMO system. Lime stone is added to coal in proportion to 1:10 and char is extracted out periodically. Bed mass represents the height of accumulated ash in the gasifier and it is removed periodically. Accordingly, the inputs and outputs of gasifier is schematically shown in Figure-1..

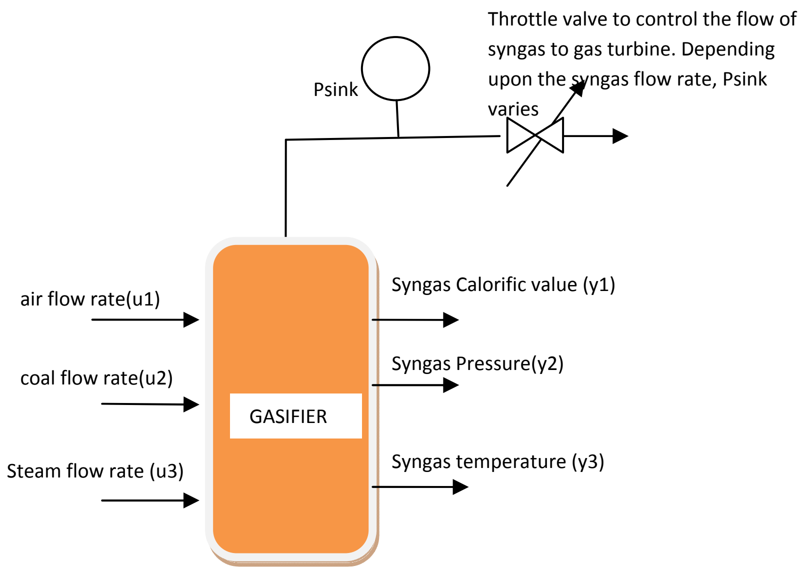

Fig1: Schematic diagram of gasifier with inputs and outputs

The ALSTOM gasifier is modelled to operate in three linear models representing three operating conditions at 0, 50 and 100% load respectively. The gasifier transfer characteristics model given by Alstom is as follows:

$$\begin{bmatrix} y1(s) \\ y2(s) \\ y3(s) \end{bmatrix} = \begin{bmatrix} G11(s) & G12(s) & G13(s) \\ G21(s) & G22(s) & G23(s) \\ G31(s) & G32(s) & G33(s) \end{bmatrix} \begin{bmatrix} u1(s) \\ u2(s) \\ u3(s) \end{bmatrix}$$

Where the denominator of G_{ij} is of 18^{th} order and the numerator is of either 16^{th} or 15^{th} order. It is desirable to reduce higher order transfer functions to lower order transfer functions.

III. REDUCED ORDER MODELLING TECHNIQUES

Working with simpler models result in faster and more reliable computations than higher-order models. Simpler models are also easier to understand and manipulate. Lower order models which are preserving the original higher order model characteristics are desirable for the study of control and optimisation purposes[50]. Many authors [26-39] underwent lower order modelling for different non linear and linear systems. The following three model reduction techniques are quite common [41,40].

- Balanced realisation using hankel singularity values
- Algebraic method
- Auxiliary method

A. Balanced Realisation using Hankel singular values

Consider the state-space representation of a linear time-invariant (LTI) system:

$$\dot{X} = Ax+Bu$$

$$Y= Cx$$

where $A \in R^{nxn}$, $B \in R^{nxp}$, $C \in R^{pxn}$ and $u \in R^{px1}$, $x \in R^{nx1}$ represents the state vector of the system. Here n denotes the order of the system and p represents the size of input vector [44].

The goal is to get the lower system given by

$$\dot{X}_r = A_r x_r + b_r u_r$$

$$Y_r = C_r x_r$$

where A∈ R^{kxk}, B ∈ R^{kxp}, C ∈ R^{pxk} and u∈ R^{px1}, x∈ R^{nx1}. r is the order of the reduced system which will be much smaller than that of the original system. The balanced truncation techniques uses order reduction by providing an L^{∞} error bound between the original and reduced systems. Two grammians P_L and Q_L are needed which are obtained by solving Lur'e equations. P_L is called controllability grammian which is the measure of how the states and outputs are coupled with each other. Q_L is called the observability grammian which measures how the states and the outputs are coupled to each other. It is proved that transformation matrix T maps the given system to balanced realization such that controllability and observability of new system (A_r B_r C_r) are equal and diagonal.

P_{Lr} = Q_{Lr} = $\sum$ =diag($\xi 1, \xi 2, \ldots \xi n,$)>0 where ($\xi 1, \xi 2, \ldots \xi n$ are called Hankel singular values

$\sum$ is portioned in to two sub matrixes

$$\sum = \begin{bmatrix} \sum 1 & 0 \\ 0 & \sum 2 \end{bmatrix}$$

Where $\sum 1 \in R^{kxk}$ and $\sum 2 \in R^{(n-k)x(n-k)}$ and new matrix is

$$A_r = T A^T -1 = \begin{bmatrix} A11 & A12 \\ A21 & A22 \end{bmatrix}$$

$$Br = TB = \begin{bmatrix} B1 \\ B2 \end{bmatrix} ,$$

$$Cr = C^T -1 = \begin{bmatrix} C1 & C2 \end{bmatrix}$$

Here L ∞ error is bounded by

$$\left\| H(s) - Hr(s) \right\| \infty <= 2 \sum_{i-k+1}^{n} \in i$$

Consider the higher order system transfer characteristics G11 of ALSTOM gasifier corresponding to 50% load

$$G11 = \frac{\begin{matrix} -1.208e+004s^{17} - 5.25e+005s^{16} - 9.387e+005s^{15} - 5.39e+006s^{14} - 1.286e005s^{13} - 1.599e004s^{12} - 1055s^{11} - 41.04s^{10} \\ -0.8994s^{9} - 0.0103s^{8} - 5.318e-005s^{7} - 9.892e-08s^{6} - 6.591e-11s^{5} - 1.281e-014s^{4} + 3.326e-018s^{3} + 1.513e-021s^{2} \\ +9.6477e-026s - 9.721e-030 \end{matrix}}{\begin{matrix} s^{18} + 43.87s^{17} + 81.23s^{16} + 49.97s^{15} + 13.44s^{14} + 1.926s^{13} + 0.1621s^{12} + 0.008369s^{11} + 2.955e-010s^{10} + 5.096e-007s^{9} \\ +5.472e-008s^{8} + 2.955e-010s^{7} 7.18e-013s^{6} + 8.62e-016s^{5} + 5.74e-019s^{4} + 2.227e-022s^{3} + 4.996e-026s^{2} \\ +5.998e-30s + 2.971e-34 \end{matrix}}$$

--------(1)

Balanced realisation can be implemented using MATLAB command RSYS = BALRED(SYS,ORDERS). Here ORDERS indicates the order of the system. The reduced order transfer function is given by,

$$g(s) = \frac{-1.839e + 005s^2 + 56.37s - 0.002357}{s^2 + 0.0005765s + 7.203e - 08}$$

B. Auxiliary method

Consider an n^{th} linear time invariant continuous higher order system represented by its transfer function as [43]:

$$G(s) = \frac{N(s)}{D(s)} = \frac{\sum_{i=0}^{n-1} A_i s^i}{\sum_{i=0}^{n} a_i s^i}$$

$$= \frac{A_{n-1}s^{n-1} + A_{n-2}s^{n-2} + \dots\dots\dots + A_2 s^2 + A_1 s + A_0}{a_n s^n + a_{n-1}s^{n-1} + \dots\dots + a_2 s^2 + a_1 s + a_0}$$

The second order transfer functions are given by

$$g(s) = \frac{A_1 s + A_0}{a_2 s^2 + a_1 s + a_0} \quad \dots\dots\dots\dots(2)$$

Consider the transfer function characteristics G11 in equation (1). Here A_0=9.647e-26; A_1= -9.721e-30; a_2=4.996e-26; a_1=5.998e-30; a_0=2.971e-34

$$g(s) = \frac{9.647e-26s - 9.721e-30}{4.996e-26s^2 + 5.998e-30s + 2.971e-34}$$

The steady state gain is given by

$$\frac{-9.721e-030}{2.971e-34} = -3.27196e-04$$

Transient gain is given by $\frac{-1.208e+04}{1} = -1.208e+04$

Objective is to maintain the steady state and approximating the transient gain.

The above equation can be represented as

$$g(s) = \frac{-1.208e+04s + B1}{1.443e-30s^2 + B2\,s + B3}$$

Divide B1,B2 , and B3 by s^2 term. Now the second order transfer function becomes,

$$G(s) = \frac{-1.208e+04s + 1.3457e-04}{s^2 + 1.2005e-04\,s + 0.59467e-08}$$

C. Algebraic Method:

The higher order transfer function is equated with the *lower* order model [42]:

$$\frac{a_{n-1}s^{n-1} + a_{n-2}s^{n-2} + \dots\dots\dots + a_0}{b_n s^m + b_{n-1}s^{m-1} + \dots\dots\dots + b_0} = \frac{A_2 s^2 + A_1 s + A_0}{B_2 s^2 + B_1 s + BA_0}$$

On cross multiplying, the equation becomes

$$(a_{n-1}s^{n-1} + a_{n-2}s^{n-2} + \dots\dots + a_0)(B_2 s^2 + B_1 s + B_0) = (b_n s^m + b_{n-1}s^{m-1} + \dots\dots + b_0)(A_2 s^2 + A_1 s + A_0)$$

The ALSTOM transfer function for G_{11} at 0% load

$$G11 = \frac{\begin{array}{l}-1.683e004s^{17} - 9.558e005s^{16} - 1.941e006s^{15} - 1.2e006s^{14} - 2.157e005s^{13} - 1.677e004s^{12} - 651.5s^{11} - 13.2s^{10} - 0.1337s^{9} \\ -0.0005759s^{8} - 7.937e-007s^{7} - 2.703e-010s^{6} + 5.053e-15s^{5} + 2.019e-017s^{4} + 4.46e-022s^{3} + 4.132e-025s^{2} + 1.537e-029s + 1.2e-034\end{array}}{\begin{array}{l}s^{18} + 57.23s^{17} + 118.4s^{16} + 76.41s^{15} + 15.72s^{14} + 1.489s^{13} + 0.07481s^{12} + 0.002126s^{11} + 3.447e-005s^{10} + 3.039e-007s^{9} + 1.287e-009s^{8} + 2.218e-012s^{7} \\ 1.62e-015s^{6} + 6.231e-019s^{5} + 1.392e-022s^{4} + 1.858e-026s^{3} + 1.443e-030s^{2} + 9.635e-040\end{array}}$$

The a_0 can be obtained by the formula

$$a_0 = \frac{\text{Sum of poles} \pm \text{Sum of zeros}}{\text{No of poles} \pm \text{No of zeros}}$$

$$a_0 = \frac{\frac{b_{m-1}}{b_m} \pm \frac{a_{n-2}}{a_{n-1}}}{m \pm n}$$

$$a_0 = \frac{57.23/1 \pm ((-9.55e+05)/(-1.68\,3e+004\ \ ))}{18 \pm 17}$$

a_0 = 10.5403, 242.4178, -9.0014, -207.0325
Taking appropriate value of a_0 , equating the powers of s,
and solving the equation the unknown values of B0,B1,B2,A1,A2 can be obtained. Thus,

$$g(s) = \frac{-\,2.966146e + 10s + 114.021444}{1762415.861223s^2 - 382735.79834s + 0.000915}$$

IV. SIMULATION RESULTS

In order to evaluate the reduced order transfer function models obtained through different methods, the unit impulse response of ALSTOM model has been taken as reference response and the responses obtained through different methods are compared and some results are shown in figure 2 to 4

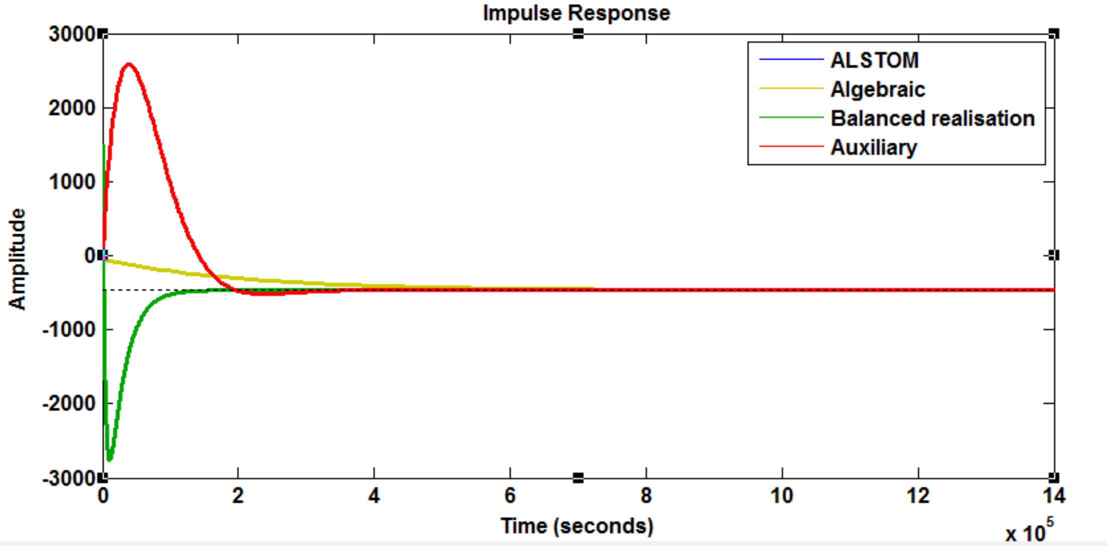

Fig 2: variation of pressure with coal flow rate

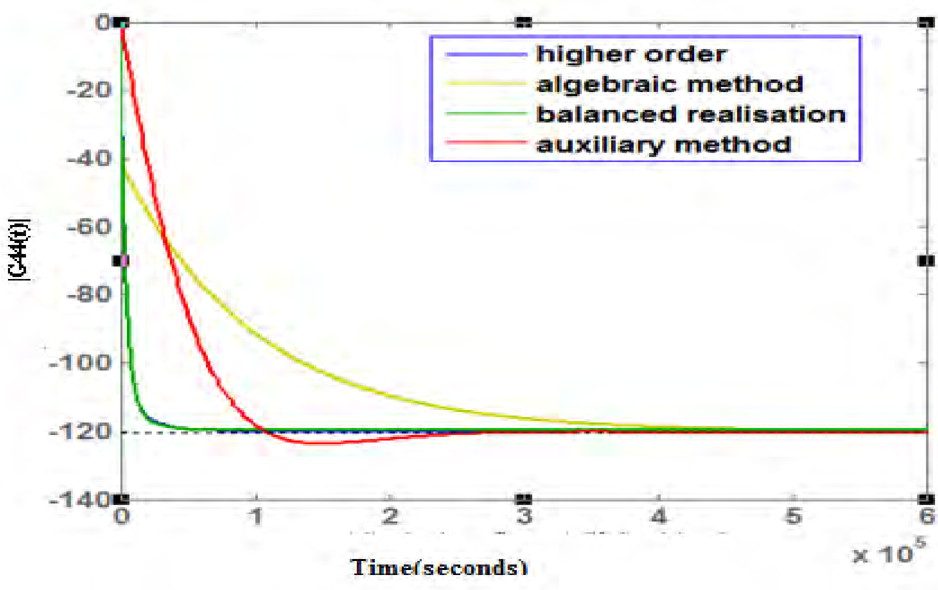

Fig 3: variation of pressure with air flow rate

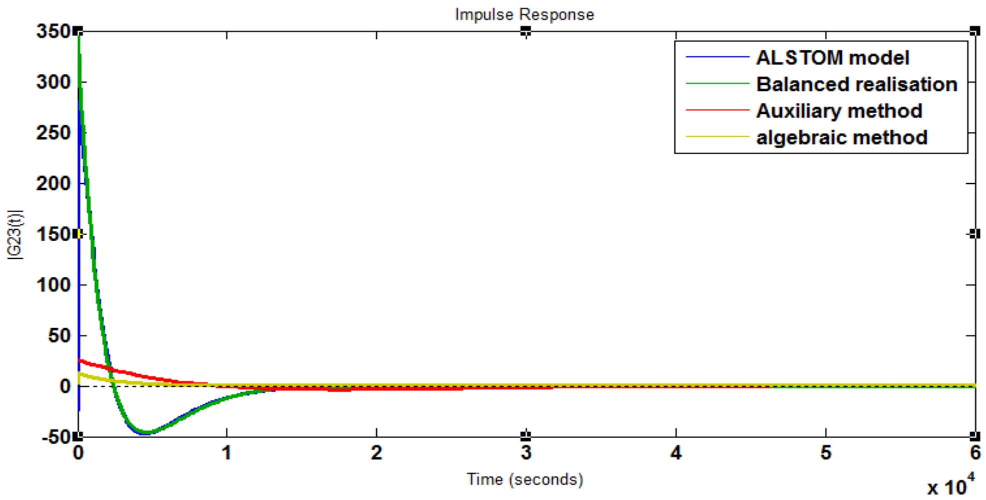

Fig 4: variation of temperature with steam flow rate

Note: the response of ALSTOM model G(t) and response obtained through balanced realisation method g(t) are closely mapped.

The errors on the basis of IAE (Integral Absolute Error) ISE (Integral Squared Error) are computed for each transfer function block obtained by balanced realisation using Hankel approximation method ,auxiliary method and algebraic method over a period of time (little above the rise time) are shown in Table 1 for all the loads.

Table 4: Integral absolute and integral square error criterion for 0% load

Transfer function characteristics	No-load			50% load			100% load		
	Balanced Realisation method	**Auxiliary method**	**Algebraic method**	**Balanced Realisation method**	**Auxiliary method**	**Algebraic method**	**Balanced Realisation method**	**Auxiliary method**	**Algebraic method**
G11	**1.63**	3.51	4.42	**0.0796**	0.828	1.1	**2.21**	7.4	9.16
G12	**1.14**	4.41	8.77	**0.783**	0.923	6.79	**1.03**	7.23	7.65
G13	**1.01**	2.21	3.29	**0.0341**	0.781	1.01	**1.4**	1.81	1.8
G21	**0.628**	1.18	3.97	**0.223**	0.922	2.62	**0.754**	0.711	1.32
G22	**3.6**	3.7	3.16	**0.0578**	0.711	1.65	**0.662**	0.54	2.52
G23	**0.06**	0.72	3.29	**0.905**	1.24	1.58	**2.95**	4.95	6.48
G31	**2.0172**	3.57	8.62	**2.63**	7.2	8.6	**0.075**	1.175	2.15
G32	**0.353**	0.372	0.397	**0.771**	1.64	1.58	**0.233**	1.233	1.9
G33	**0.03489**	0.789	7.689	**2.74**	2.94	5.91	**1.84**	1.72	1.659

V. PERFORMANCE TESTS AND DISCUSSION:

Table 1 shows that balanced realisation method is superior to other methods.

Also in order to approximate the higher order transfer functions, with the second order transfer functions, the following time domain parameters are vital.

- Rise time
- Settling time
- Peak response
- Steady state value

The transient response characteristics results between ALSTOM gasifier and the balanced realisation method are given in table 2 for no-load condition. Similar tabular column can be obtained for 50% and 100% load . It is found that balanced realisation method retains all the important transient time characteristics of the original system and approximates its response as closely as possible for the same type of inputs.

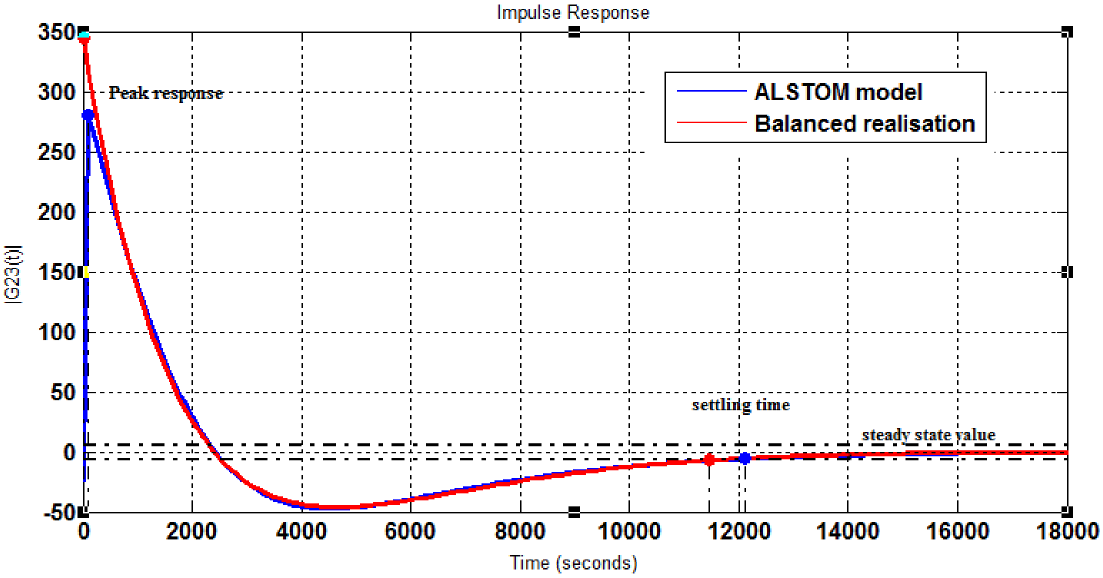

Figure 5: transfer function characteristics with time domain parameters

Table 2: Time domain parameter response for 0% load

Transfer functions	Peak response time		Settling time		Steady state value		Rise time	
	Higher Order	Balanced realisation	Higher Order	Balanced realisation	Higher Order	Balanced realisation	Higher Order	Balanced realisation
G11	-4.99E+05	-4.38E+05	8.45E+04	2.78E+03	1.25E+05	1.24E+05	736	9.23E+04
G 12	-1.29E+06	-1.30E+06	1.04E+05	1.07E+05	-3.74E+05	-3.74E+05	7.73E+02	1.70E+03
G 13	9.08E+05	9.08E+05	3.36E+04	2.76E+04	-3.42E+05	-3.42E+05	2.11E+04	1.12E+04
G 21	4.22E+03	4.25E+03	1.04E+05	1.06E+05	1.48E+03	1.48E+03	947	940
G 22	-2.73E+03	-2.76E+03	1.04E+05	1.07E+05	-4.66E+02	-4.66E+02	4.10E+02	1.53E+03
G 23	7.63E+03	6.90E+03	2.88E+04	2.81E+04	3.93E+03	3.93E+03	5.22E+00	1.12E+04
G 31	88.3	87.8	8.43E+04	9.52E+04	60.4	60.4	2.36E+03	2.56E+03
G 32	-170	-171	1.04E+05	1.07E+05	-79.7	-79.7	1.46E+03	1.46E+03
G 33	-120	-120	3.34E+04	2.85E+04	-120	-120	1.04E+04	1.13E+04
G d1	4.74E+03	-2.31E-01	8.23E+04	1.01E+05	-0.072	-0.072	2.18E+02	5.18E+04
G d2	0.986	0.986	5.53	9.79e+04	0.986	0.986	4.51	5.27e+04
G d3	-2.68E+03	-2.20E-05	8.26E+04	1.01E+05	-6.35E-06	-6.35E-06	190	5.19E+04

VI. CONCLUSION:

Most of the lower order model techniques stem from the idea of matching the steady state gain or transient gain or both. It is more important that the time domain parameters also to be satisfied. The simulation and tabulation results show that only balanced realisation method has lesser IAE error and give better approximation to the higher order models. This is due to the fact that balanced realisation method not only satisfies steady state gain but also transient characteristics such as peak response time, rise time and settling time. It is believed that the models derived by balanced realisation method given in annexure 1 will become basis for further research on Gasifier control. The authors have investigated with these lower order models and obtained very good results for the two challenge problem posed on gasifier control and the results will be published separately. These lower order models may also be used by researchers with different control algorithm to see the performance of the gasifier

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REFERENCES

[1] Pike A.W., Donne M.S and Dixon.R, "Dynamic modelling and simulation of the air blown gasification cycle prototype publication, 1998, 457,York university pp 354-361.
[2] Dixon.R "Advanced gasifier control, computing and control engineering " journal IEE (1999) ,10(3) pp 93-96.
[3] Rice M,Rosster.J and schurmans J "An advanced predictive control approach to the Alstom gasifier problem", proc, Inst. Mech integrated plant" in proceedings of the international conference on simulation, IEE Eng.I,J.System control Eng., ,2000, 214 pp.405-413
[4] E.Prempain, I.Postlethwaite and XD sun "Robust control of the gasifier using a mixed H_∞ approach" proc, Inst.Mech Eng.I,J.System control Eng., 2000,214 pp.415-426
[5] BN Asmar, WE Jones and Ja Wilson, "A process engineering approach to the alstom gasifier problem" proc, Inst.Mech Eng.I,J.System control Eng., 2000, 214 pp.441-452.
[6] N Munro, JM Edmunds, E.Kontogianees and St Impram " A sequential loop closing approach to the Alstom gasifier problem" proc, Inst.Mech Eng.I,J.System control Eng., 2000, 214 pp.427-439.
[7] Dixon R "Alstom Benchmark challenge II: control of Nonlinear Gasifier model", 2002 http://www.iee.org/omcomms/PN/controlauto/Specification_v2.pdf
[8] Dixon R, "Benchmark challenge at control,", Comput. Control Eng IEE, 2004, 10(3) pp 21-23
[9] R.Kotteeswaran, L.Sivakumar, "Partial-retuning of decentralised PI Controller of nonlinear multivariable process using Firefly algorithm", IEEE International Conference on Human Computer Interactions (ICHCI'13), Saveetha University, 23-24th Aug 2013, Chennai, India
[10] L.Sivakumar, R.Kotteeswaran, "Soft computing based partial-retuning of decentralised PI Controller of nonlinear multivariable process", ICT and Critical Infrastructure: Proceedings of the 48th Annual Convention of Computer Society of India- Vol I, Advances in Intelligent Systems and Computing Volume 248, 2014, pp 117-124
[11] R.Kotteeswaran, L.Sivakumar, "Normalized Normal Constraint algorithm based Multi- Objective optimal tuning of Decentralised PI controller of Nonlinear Multivariable Process – Coal gasifier", SEMCCO 2013, 'Lecture Notes in Computer Science', Vol 8297, 2013
[12] R.Kotteeswaran, L.Sivakumar, "Optimal Partial-retuning of decentralised PI controller of coal gasifier using Bat Algorithm", SEMCCO 2013, 'Lecture Notes in Computer Science', Vol 8297, 2013
[13] R.Kotteeswaran, L.Sivakumar, "A Novel Bat Algorithm Based Re-Tuning of PI Controller of Coal Gasifier for Optimum Response", MIKE 2013 'Lecture Notes in Artificial Intelligence(LNAI), Vol 8284, 2013.
[14] R.Kotteeswaran, L.Sivakumar, "Performance Evaluation of Optimal PI Controller for ALSTOM Gasifier during Coal Quality variations", Journal of Process Control, DOI 10.1016/j.jprocont.2013.10.006
[15] Griffin, I. A., Schroder, P., Chipperfield, A. J., and Fleming, P. J, Multi-objective optimization approach to the ALSTOM gasifier problem, Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, 214(6) (2000) 453–469.
[16] Liu, G. P., Dixon, R., & Daley, S, 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, 214(6) (2000) 395–404.
[17] Simm, A and Liu,GP, Improving the performance of the ALSTOM baseline controller using multiobjective optimisation, IEE Proceedings - Control Theory and Applications, 153(3) (2006) 286–292.
[18] Nobakhti A, Wang H, A simple self-adaptive Differential Evolution algorithm with application on the ALSTOM gasifier, Applied Soft Computing, 8(1) (2008) 350–370.
[19] Xue Y, Li D, Gao F, Multi-objective optimization and selection for the PI control of ALSTOM gasifier problem, Control Engineering Practice, 18(1) (2010) 67–76.
[20] Chin CS, Munro N, Control of the ALSTOM gasifier benchmark problem using H2 methodology, Journal of Process Control, 13(8) (2003) 759–68.
[21] Al Seyab RK, Cao Y, Nonlinear model predictive control for the ALSTOM gasifier, Journal of Process Control, 16(8) (2006) 795–808.
[22] Agustriyanto R, Zhang J, Control structure selection for the ALSTOM gasifier benchmark process using GRDG analysis, International Journal of Modelling, Identification and Control, 6(2) (2009) 126-135.
[23] Tan W, Lou G, Liang L, Partially decentralized control for ALSTOM gasifier, ISA transactions, 50(3) (2011) 397–408.
[24] Huang C, Li D, Xue Y, Active disturbance rejection control for the ALSTOM gasifier benchmark problem, Control Engineering Practice, 21(4) (2013) 556–564.
[25] R.K. Seyab, Y.Cao and S.H Yang, "The second alstom benchmark challenge on gasifier control predictive control for the ALSTOM gasifier problem" IEE proceedings on control theory, vol153, N03 May 2006.
[26] L. Sivakumar and Anitha Mary.X , "A low order transfer function model for MIMO ALSTOM gasifier", IEEE international conference on process modelling, control and automation, Coimbatore Institute of Technology, Coimbatore, India, July 2011,pp 1-6 http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5978899&isnumber=5978855

[27] L. Sivakumar and X. Anithamary (2012) "Lower Order Modeling and Control of Alstom Fluidized Bed Gasifier" chapter 13, INTECH publication on Gasifier and it practical applications,pp 1-26 http://www.intechopen.com/books/gasification-for-practical-applications/lower-order-modeling-and- control-of-alstom-fluidized-bed-gasifier

[28] Anitha Mary.X L.Sivakumar , " A Reduced Order Transfer Function Models for Alstom Gasifier using Genetic Algorithm " International Journal of Computer Applications (0975 – 8887) , 2012, 46(5), pp 1-6 http://www.ijcaonline.org/archives/volume46/number5/6906-9300

[29] Haryanto, P. Siregar, D. Kurniadi, and Keum-Shik Hong, "Development of Integrated Alstom Gasification Simulator for Implementation Using DCS CS3000", Proceedings of the 17th World Congress, the International Federation of Automatic Control, Seoul, Korea, July 2008, pp 6-11.

[30] R.Kotteeswaran, L.Sivakumar " Lower order transfer function identification of Nonlinear MIMO system-Alstom Gasifier", International Journal of engineering research and applications,2012, 2(4), pp 1220- 1226.

[31] R.Kotteeswaran, L.Sivakumar, 'Linear Identification of Nonlinear MIMO system-Alstom Gasifier', First international conference on Modern Trends in Instrumentation and Control(ICIC2011), PSG College of Technology, 2-3 Sep 2011.

[32] Sivakumar, L, Reddy K.L and Sundararajan. N, "Detailed circulation analysis to determine the DNB margin in natural circulation boilers" Proceedings of International conference on Heat and Mass Transfer Hyderabad), Feb 13- 16 1980, p 1-8.

[33] Ponnusamy.P,Sivakumar, L. and Sankaran, S. V."Low-order dynamic model of a complete thermal power plant loop", Proceedings of the Power Plant Dynamics,Control and Testing Symposium, Vol. 1, 1983, p 10. 01-10.

[34] Sivakumar. L.andBhattacharya. R. K, "Dynamic analysis of a power boiler using a Nonlinear mathematical model", Proceedings of second symposium on Power Plant Dynamics and Controls, Hyderabad (Record of Proceedings), Feb 14-16, 1979, p 21-29.

[35] Sivakumar. L and Ganpathiraman. G "Performance analysis diagnostics and optimisation generation", Conference on: IT Power-Improving Performance And Productivity, NewDelhi ; Sep 2006.

[36] Yadaiah. N, Deekshatulu.B,.L, sivakumar.L, Rao, V.S.H., "Neural network algorithm for parameter identification of dynamical systems involving time delays", Applied soft computing journal Vol. 224, no.1 pp. 59-67, 2010.

[37] Yadaiah. N, sivakumar.L, Deekshatulu.B,.L, " Parameter identification via neural networks with fast convergence" Mathematics and Computer in Simulation, vol.51, no.3-4, pp. 157-167, 2000.

[38] Ganti Prasad Rao, Sivakumar Lingappan, " Order and parameter identification in continuous linear systems via walsh function", Proceedings of IEEE, vol 70, no.7, 764-766, 1982.

[39] Ganti Prasad Rao, Sivakumar Lingappan, "Transfer function matrix identification in MIMO systems via walsh function", Proceedings of IEEE, Vol.69, no.4, pp.465-466, 1981.

[40] H. Sandberg and R. M. Murray "Model reduction of interconnected linear systems" OPTIMAL CONTROL APPLICATIONS AND METHODS 2007;

[41] Dmitry Missiuro Vasilyev," Theoretical and practical aspects of linear and nonlinear model order reduction techniques" thesis MASSACHUSETTS INSTITUTE OF TECHNOLOGY, February 2008

[42] P.Poongodi, S. Victor Genetic algorithm based PID controller design forLTI system via reduced order model, International Conference on Instrumentation, Control & Automation ICA2009 October 20-22, 2009, Bandung, Indonesia.

[43] S.N. Sivanandam, S.N.Deepa, A Comparative Study Using Genetic Algorithm andParticle Swarm Optimization for Lower Order System Modelling International Journal of the Computer, the Internet and Management Vol. 17. No.3 pp 1 -10, (September – December, 2009.

[44] Peter benner,Roland W. Freund, Danny C.Sornsen, Andras Varga, Special issues on "order reduction of large-scale systems" www.mpi-magdeburg.mpg.de/mpcs/benner/../laa_mor_perface.pdf

Annexure -1

Transfer function characteristics using balanced realisation method

0% load	50% load	100% load
$G11=\frac{-1330s^2+395.4s+0.006024}{S^2+0.0005765s+7.203e-08}$	$G11=\frac{3.828e004s^2+561.7s+0.006739}{s^2+0.0002741s+9.897e-009}$	$G11=\frac{-1.341e004s^2+332.9s+0.006836}{s^2+0.0008394s+2.067e-007}$
$G12=\frac{2.476s^2+5.647s+0.0007864}{S^2+0.0005765s+7.203e-08}$	$G12=\frac{79.85s^2-0.955s-0.0003939}{s^2+0.0002741s+9.897e-009}$	$G12=\frac{-1.569s^2-1.064s-0.0012}{s^2+0.0008394s+2.067e-7}$
$G13=\frac{199.6s^2+5.647s+0.00005637}{S^2+0.0005765s+7.203e-08}$	$G13=\frac{178.3s^2+1.338s+1.467e-005}{s^2+0.0002741s+9.897e-009}$	$G13=\frac{-91.6s^2+11.2s-0.0001045}{s^2+0.0008394s+2.067e-7}$
$G14=\frac{0.3227s^2+0.06097s+4.256e-007}{S^2+0.0005765s+7.203e-08}$	$G14=\frac{3.845s^2+0.05121s+5.082e-007}{s^2+0.0002741s+9.897e-009}$	$G14=\frac{-2.133s^2+0.06858s-3.005e-7}{s^2+0.0008394s+2.067e-7}$

$G21=\frac{-1.839e-005s^2+56.37s-0.002357}{S^2+0.0005765s+7.203e-08}$	$G21=\frac{-4.377e005s^2+120.2s+0.001232}{S^2+0.0002741s+9.897e-009}$	$G21=\frac{-1.09e005s^2+44.24s-0.008757}{S^2+0.0008394s+2.067e-007}$
$G22=\frac{166s^2-0.06141s-0.0001875}{S^2+0.0005765s+7.203e-08}$	$G22=\frac{948.2s^2+0.117s-9.333e-005}{S^2+0.0002741s+9.897e-009}$	$G22=\frac{-98.55s^2-0.1299s-0.0003198}{S^2+0.0008394s+2.067e-007}$
$G23=\frac{8739s^2+7.32s+0.0007719}{s^2+0.000576s+7.203e-08}$	$G23=\frac{4701s^2+1.852s+5.905e-005}{S^2+0.0002741s+9.897e-009}$	$G23=\frac{1.122e004s^2-13.9s-0.002761}{S^2+0.0008394s+2.067e-007}$
$G24=\frac{8.171s^2+0.02981s+2.14e-006}{S^2+0.0005765s+7.203e-08}$	$G24=\frac{11.85s^2+0.02519s+5.973e-007}{S^2+0.0002741s+9.897e-009}$	$G24=\frac{7.827s^2+0.03453s+4.369e-006}{S^2+0.0008394s+2.067e-007}$
$G31=\frac{2.322e005s^2-243.4s+0.001665}{S^2+0.0005765s+7.203e-08}$	$G31=\frac{5.378e005s^2-408.2s-0.003703}{S^2+0.0002741s+9.897e-009}$	$G31=\frac{1.525e005s^2-172.4s+0.007875}{S^2+0.0008394s+2.067e-007}$
$G32=\frac{-375.9s^2+0.4627s+0.0005865}{S^2+0.0005765s+7.203e-08}$	$G32=\frac{-1552s^2+0.2945s+0.0003176}{S^2+0.0002741s+9.897e-009}$	$G32=\frac{-175.7s^2+0.4979s+0.0008291}{S^2+0.0008394s+2.067e-007}$
$G33=\frac{2926s^2-3.597s+3.286e-005}{S^2+0.0005765s+7.203e-08}$	$G33=\frac{1502s^2-0.8885s-4.612e-006}{S^2+0.0002741s+9.897e-009}$	$G33=\frac{3859s^2-6.647s-0.0001527}{S^2+0.0008394s+2.067e-007}$
$G34=\frac{-0.4876s^2-0.0597s+3.286e-05}{S^2+0.0005765s+7.203e-08}$	$G34=\frac{-5.796s^2-0.05223s-7.889e-007}{S^2+0.0002741s+9.897e-009}$	$G34=\frac{1.243s^2-0.06065s-3.748e-06}{S^2+0.0008394s+2.067e-007}$
$G41=\frac{3.296e005s^2+24.4s-0.006982}{S^2+0.0005765s+7.203e-08}$	$G41=\frac{9.186e005s^2-25.51s-0.003382}{S^2+0.0002741s+9.897e-009}$	$G41=\frac{1.973e005s^2+56.79s-0.008404}{S^2+0.0008394s+2.067e-007}$
$G42=\frac{72.72s^2-0.4004s-7.935e-005}{S^2+0.0005765s+7.203e-08}$	$G42=\frac{45.08s^2-0.4357s-3.123e-005}{S^2+0.0002741s+9.897e-009}$	$G42=\frac{83.77s^2+0.4462s-0.0001526}{S^2+0.0008394s+2.067e-007}$
$G43=\frac{1.258e004s^2+4.893s+0.0004882}{S^2+0.0005765s+7.203e-08}$	$G43=\frac{6900s^2+1.238s+3.885e-005}{S^2+0.0002741s+9.897e-009}$	$G43=\frac{1.582e004s^2+9.574s+0.001606}{S^2+0.0008394s+2.067e-007}$
$G44=\frac{1.715s^2-0.02503s-4.705e-006}{S^2+0.0005765s+7.203e-08}$	$G44=\frac{-4.063s^2-0.02662s-1.191e-06}{S^2+0.0002741s+9.897e-009}$	$G44=\frac{3.614s^2-0.0201s-9.644e-006}{S^2+0.0008394s+2.067e-007}$

$Gd1=\frac{0.1224s^2-2.013e-05s+9.669e-09}{S^2+0.0005765s+7.203e-08}$	$Gd1=\frac{-0.1992s^2-7.057e-5s-7.12e-10}{S^2+0.0002741s+9.897e-009}$	$Gd1=\frac{0.1274s^2-4.698e-5s-3.358e-8}{S^2+0.0008394s+2.067e-007}$
$Gd2=\frac{9.213e-5s^2+3.538e-7s+2.198e-10}{S^2+0.0005765s+7.203e-08}$	$Gd2=\frac{-0.0003971s^2+6.56e-8s+4.34e-011}{S^2+0.0002741s+9.897e-009}$	$Gd2=\frac{-1.287e-5s^2+0.4462s-0.000152}{S^2+0.0008394s+2.067e-007}$
$Gd3=\frac{0.9534s\hat{}2+0.0005484s+6.87e-8}{S^2+0.0005765s+7.203e-08}$	$Gd3=\frac{0.9858s^2+0.0002702s+9.76e-009}{S^2+0.0002741s+9.897e-009}$	$Gd3=\frac{0.9264s^2+0.0007726s+1.918e-7}{S^2+0.0008394s+2.067e-007}$
$Gd4=\frac{-3.39e-5s^2-3.341e-8s-2.163e-12}{S^2+0.0005765s+7.203e-08}$	$Gd4=\frac{-1.935e-5s^2-6.714e-9s-6.282e-14}{S^2+0.0002741s+9.897e-009}$	$Gd4=\frac{-4.358e-5s^2-6.78e-8s-6.799e-14}{S^2+0.0008394s+2.067e-007}$