A Reduced Order Transfer Function Models for Alstom Gasifier using Genetic Algorithm

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ABSTRACT
ALSTOM has thrown a challenge problem related to the control of MIMO gasifier which is a nonlinear system. Quite a few researchers have tried different methods for control tuning and found that critical process transients such as pressure and temperature of syngas during specified load changes are not within the desired limits. This is mainly attributed to a very high order of the gasifier system. Due to this, efforts have been made to represent gasifier higher order models as a simplified lower order models. This paper focuses on identifying a reduced order transfer function models for gasifier with minimum IAE and ISE error criterion using Genetic Algorithm. The lower order transfer functions obtained using Genetic Algorithm is found to be superior to those obtained using RGA loop pairing and Algebraic method proposed respectively by Haryanto and Sivakumar et.al.

Keywords:
Gasifier, Reduced order transfer function, Algebraic Method, Genetic Algorithm, MIMO Systems.

1. INTRODUCTION
Integrated Gasification Combined Cycle (IGCC) is being developed all over the world to provide higher conversion efficiency than the conventional power generation with reduced pollutant emissions. Here coal is converted into fuel gas which in turn is used to produce electricity. The ALSTOM gasifier, one of the components in IGCC is found to be a complicated nonlinear process. Two challenges were issued by ALSTOM in 1997 and 2003 respectively. The objective of the challenges is to design a controller for gasifier which satisfies the performance criteria viz pressure and temperature transients of syngas to be well within the specified limits during load changes. The controllers like predictive control[3] multi objective optimitization [4], proportional integral plus control [5], multi objective optimal tuning PI controller design [6], H∞ control [7], process engineering approach[8], sequential loop closing approach [9] are suggested for first challenges. Initial attempts to control the gasifier were presented at a meeting [2] on 24 July 1998 at Coventry University. None of the controllers discussed at the meetings met the performance criteria. Multi loop PI controller, Model predictive control [12], wiener model [13] are suggested for second challenges[10,11]. Analysis of these controllers suggested that it is difficult to control such complicated higher order systems and motivated researchers to obtain lower order transfer function models. It is observed that Haryanto et.al., [14], Sivakumar and Anitha Mary.X [15], Sivakumar and Koteeswaran [16] developed lower order transfer function models for ALSTOM MIMO system. The low order transfer function models developed by authors [15] using algebraic method are found to be better approximation than those by Haryanto et.al., and reflects the characteristics of original higher order system. However, four transfer functions out of sixteen transfer functions obtained by Algebraic method are having higher error than those by Haryanto et.al, This paper extends the work of authors [15] using genetic algorithms to obtain reduced order transfer functions with minimum ISE and IAE error.

2. GASIFIER DESCRIPTION
ALSTOM gasifier consists of 5 input and 4 output system. Char extraction flow rate (u1), air flow rate (u2), coal flow rate (u3), steam flow rare (u4) and limestone flow rate (u5) are the controllable inputs, Syngas calorific value (y1), bed mass (y2), pressure (y3) and temperature (y4) are the controllable output. Limestone and coal are added in the ratio of 1:10. This leaves gasifier with 4x4 MIMO system.Figure 1 shows the ALSTOM gasifier with input and output variable.
The ALSTOM gasifier is modeled in state space form as given by

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

$$Y=Cx+Du$$

Where
x = Internal states of gasifier, a column vector with dimension 25x1
u = Input variables, a column vector with dimension 6x1
A = system matrix governing the process dynamics, a square matrix with dimension 25x25
B = Input matrix with dimension 25x6
Y = Output variables, a column vector with dimension 4x1
C = Observable matrix with dimension 25x4
D = disturbance matrix with dimension 4x6

The values of A, B, C, D, x(0), Y for three different loads-100%, 50% and no-load are available in the following link:

(http://www.ieee.org/OnComms/PN/controlauto/benchmark.cfm.)

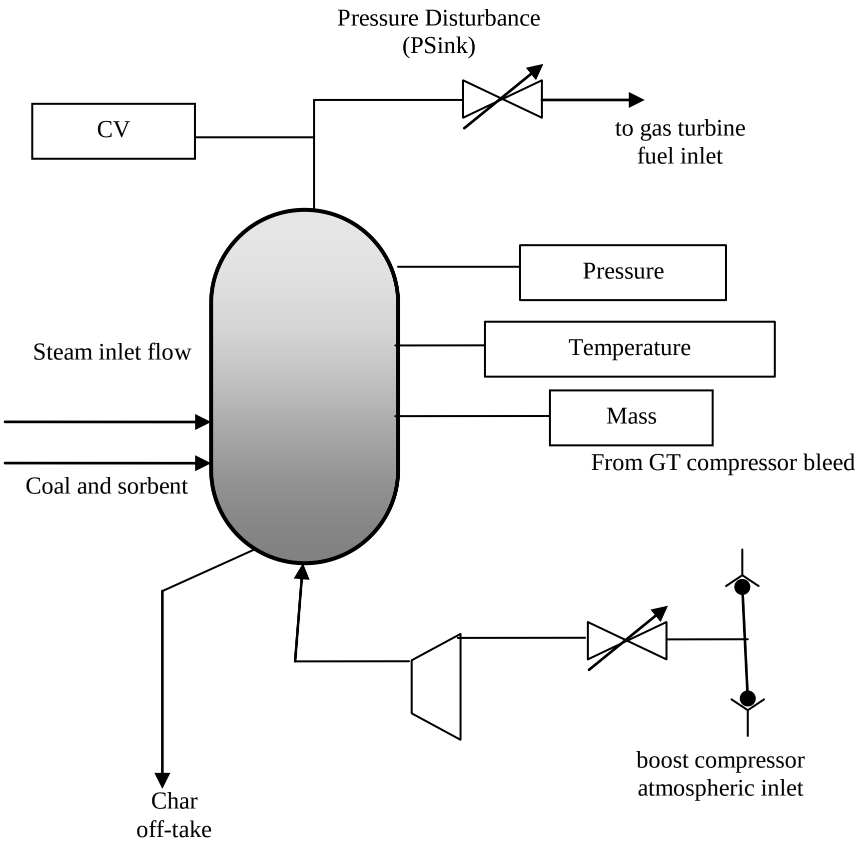

Fig 1: ALSTOM Gasifier

3. HIGHER ORDER TRANSFER FUNCTION MODELS

On analyzing the ALSTOM gasifier model, the model is found to be more complex and it contains very high cross-coupling between input and output [10]. The state space equation is converted to transfer function models using MATLAB command sys = ss(a,b,c,d) and [num,den]=ss2tf(a,b,c,d,1). After conversion by Matlab command, the system is described in s- domain as follows:

$$\begin{bmatrix} y1(s) \\ y2(s) \\ y3(s) \\ y4(s) \end{bmatrix} = \begin{bmatrix} G11(s) & G12(s) & G13(s) & G14(s) \\ G21(s) & G22(s) & G23(s) & G24(s) \\ G31(s) & G32(s) & G33(s) & G34(s) \\ G41(s) & G42(s) & G43(s) & G44(s) \end{bmatrix} \begin{bmatrix} u1(s) \\ u2(s) \\ u3(s) \\ u4(s) \end{bmatrix}$$

where

yi(s) = output variables ; i={1,4 }

Gij(s) = transfer characteristic between j^{th} output due to i^{th} input ; i= {1,4} ; j={1,4}

ui(s) = input variable ; i={1,4}

It is to be noted that the denominator polynomial of each element G_{ij} is of 24^{th} order while the numerator is of order less than or equal to 23^{rd}. A typical transfer characteristic between an output (syngas pressure) due to all inputs is shown in block diagram as in figure 2.

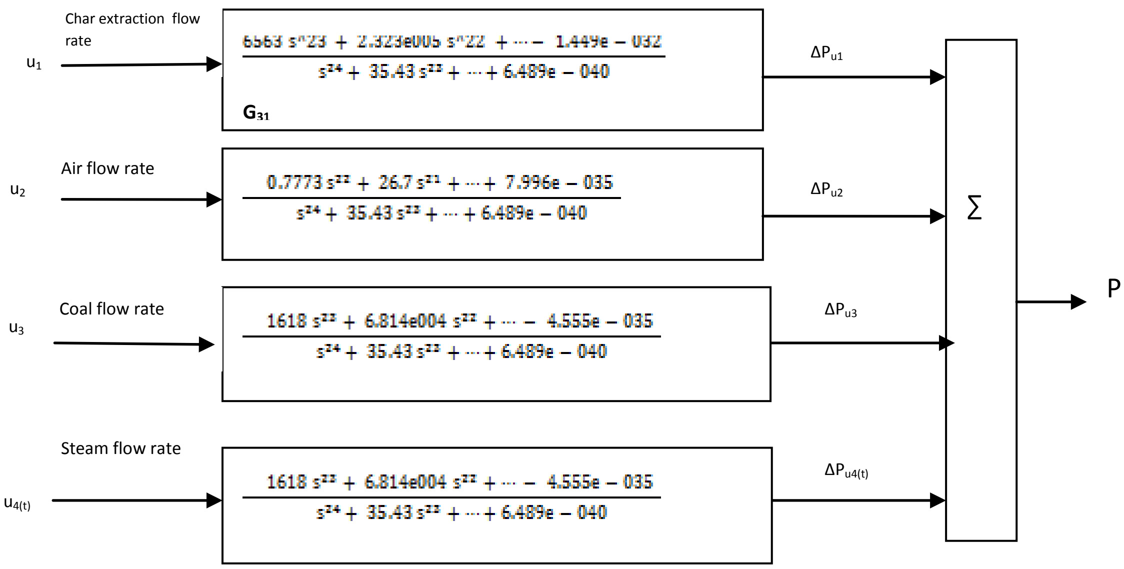

Figure 2 Transfer characteristic between pressure due to all inputs

$P(t) = P_{steady\ state} + \Delta P_{u1} + \Delta P_{u2} + \Delta P_{u3} + \Delta P_{u4}$

Here ΔP_{ui} is the incremental change due to different inputs u_i. Thus

ΔP_{u1} is the incremental change in pressure due to steady state change in char extraction flow rate,

ΔP_{u2} is the incremental change in pressure due to steady state change in Air flow rate,

ΔP_{u3} is the incremental change in pressure due to steady state change in Coal flow rate and

ΔP_{u4} is the incremental change in pressure due to steady state change in steam extraction flow rate. The output is given below

Now the problem boils down to the reduction of higher order transfer function models obtained by MATLAB command to lower order transfer function models by the application of algebraic method and genetic algorithm.

4. ALGEBRAIC METHOD

The higher order transfer can be equated with second order transfer function.

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

On cross multiplying, the equation becomes

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

The A_0 can be obtained as illustrated [17] as

$$A_0 = \frac{Sum\ of\ \text{poles} \pm \text{Sum of zeros}}{\text{No of poles} \pm \text{No of zeros}}$$

$$A_0 = \frac{b_{m-1}/b_m \pm a_{n-2}/a_{n-1}}{m \pm n}$$

Taking appropriate value of A_0, equating the powers of s, and solving the equation the unknown values of B0, B1, A1, A2 can be obtained. Appendix 1 gives the lower order transfer function models using Algebraic method. The errors on the basis of IAE (Integral Absolute Error) and ISE (Integral Squared Error) are computed for each transfer function block obtained by algebraic method and RGA loop pairing aare taken over a period of time (little above the rise time). Table 1 shows the IAE and ISE error criterion for the lower order transfer functions using Algebraic method, and transfer function obtained using RGA loop pairing for 100% load[15]. During the process of identifying transfer function, the ISE and IAE associated with the transfer characteristics of :

- First output with second input ie.,(G21)
- First output with third input ie.,(G31)
- First output with fourth input (G41)
- Third output with first input (G13)

are seems to be very high. It would be better if we avoid these higher error and this motivated an alternate lower order model to be derived specially for G21, G31, G41 and G13. The present lower order transfer function in table 1 with high ISE and IAE shown in bold are further re-identified using genetic algorithm leading to very simple low order models.

TABLE 1 : IAE AND ISE ERROR CRITERION FOR ALGEBRAIC AND RGA LOOP PAIRING METHODS

Transfer function	Integral Absolute error		Integer Squared error	
	TF obtained using Algebraic method	TF obtained using RGA loop pairing method	TF using Algebraic method	TF using RGA loop pairing method
G11	1644	1.087e+004	2.16e+006	1.455e+007
G12	7.09	2.954e+005	7.606	1.12e+010
G13	4.828e+004	8.039e+004	**7.98e+008**	**7.784e+008**
G14	5.096	2.308e+005	5.85	6.955e+009
G21	**2.868e+005**	**8.71e+004**	**1.157e+10**	**8.637e+009**
G22	11.5	20.97	20.74	57.78
G23	50.56	6.8e+004	1018	5.145e+008
G24	73.09	114.2	1412	2555
G31	**9.128e+006**	**8.799e+006**	**2.166e+13**	**2.519e+013**
G32	0.4021	6.277e+004	0.0362	4.58e+008
G33	35.04	9250	283.1	9.1e+006
G34	2.549	1.086e+005	0.8598	1.344e+009
G41	**1.437e+007**	**1.434e+007**	**8.005e+13**	**7.98e+013**
G42	15.18	2.695	39.14	1.213
G43	462.3	1.133e+005	3.812e+004	1.46e+009
G44	1.683	0.4994	0.3358	0.1532

5. GENETIC ALGORITHM

In recent years, evolutionary computation has extented its growth in engineering field especially in optimization problems[19]. Genetic Algorithm is one such optimization tool and found to give better lower order approximation that reflects the characterization of higher order system.

LOWER ORDER MODELLING:

Appendix 2 gives the auxiliary scheme for low order model [18]

The ALSTOM higher order transfer function for G13 is given below:

G13=

$$\frac{\begin{gathered}-1.1s^{23}-12.44s^{22}+2893s^{21}+2764s^{20}+1212s^{19}+324.2s^{18}+59.29s^{17}+\\ 7.864s^{16}+0.7827s^{15}+0.05961s^{14}+0.003508s^{13}+0.00016s^{12}\\ +5.623e-006s^{11}+1.505e-007s^{10}+3e-009s^{9}+4.293e-011s^{8}\\ 4.155e-013s^{7}+2.4446e-015s^{6}+6.972e-018s^{5}+4.046e-021s^{4}\\ +8.036e-024s^{3}-1.1772e-026s^{2}-5.48e-030\,s+8.511e-034\end{gathered}}{\begin{gathered}s^{24}+35.38s^{23}+78.31s^{22}+68.51s^{21}+32.81s^{20}+9.998s^{19}+2.106s^{18}+\\ 0.3225s^{17}+0.03703s^{16}+0.00325s^{15}+0.0002203s^{14}+1.156e-005s^{13}\\ 4.687e-007s^{12}+1.45e-008s^{11}+3.36e-010s^{10}+5.64e-012s^{9}\\ 6.52e-014s^{8}+4.785e-016s^{7}+1.95e-18s^{6}+3.99e-021s^{5}+\\ 4.505e-024s^{4}+2.982e-024s^{3}+1.148e-030s^{2}+2.389e-034s+\\ 2.078e-038\end{gathered}}$$

The second approximation is given as [18]

$$G13=\frac{5.48e-30s\ -8.511e-034}{1.148e-30s^{2}+2.389e-034s+2.076e-038}$$

The transient and steady state gain for G13 is

$$TG/_{G13(s)}=\frac{-1.1}{1}\ =\ -1.1$$

$$SSG/_{G13(s)}=\frac{8.511e-34}{2.076e-38}=\ 4.0997e+04$$

The auxiliary scheme given in appendix 2 is used to find R(s) from G(s)

$$R(s)\ =\ \frac{-5.48e-030\ s+8.511e-034}{1.148e-030\,s^{2}+2.389e-034s+2.078e-038}$$

The above equation should be tuned to satisfy the transient and steady state gain so that R(s) reflects the characteristics of G(s)

$$R(s)=\frac{-1.1\,s-7.4137631e-04}{s^{2}+\ 2.081e-04s+1.8083624e-08}$$

$$=\frac{B_1\,s+B_0}{b_2s^{2}+b_1\,s+b_0}$$

The parameters B0 = -7.4137631e-04, b1= 2.081e-04 and b0= 1.8083624e-08 are used as seed value for genetic algorithm with ISE error as the objective function. The ISE error (E) can be obtained by taking the sum of the square of the difference between the step response of higher and lower order transfer function. The ISE error is given by

$$E=\sum_{t=0}^{\tau}(Y_t - y_t)^2$$

where, Yt is the unit step time response of the higher order system at the t^{th} instant in the time interval $0\leq t\leq\tau$, where τ is to be chosen and y_t is the unit step time response of the lower order system at the t^{th} time instant. The matlab commands

```
options =gaoptimset('InitialPop', [B1 B2 B3])
[x fval output reasons] = ga(@objectivefun, nvars,options)
```

are used with ISE error as objective function. Here the population is set at 20 individuals and the maximum generation is 51. The crossover fraction is 0.8. Similarly the lower order models G31, G21 and G41 corresponding to higher order models specified by ALSTOM can be obtained. Table 2 shows the minimum IAE and ISE error criterion obtained using Genetic Algorithm and it is found that error is minimum when compared to transfer function obtained using RGA loop pairing. Fig 2 shows the flowchart for lower order modeling using Genetic Algorithm.

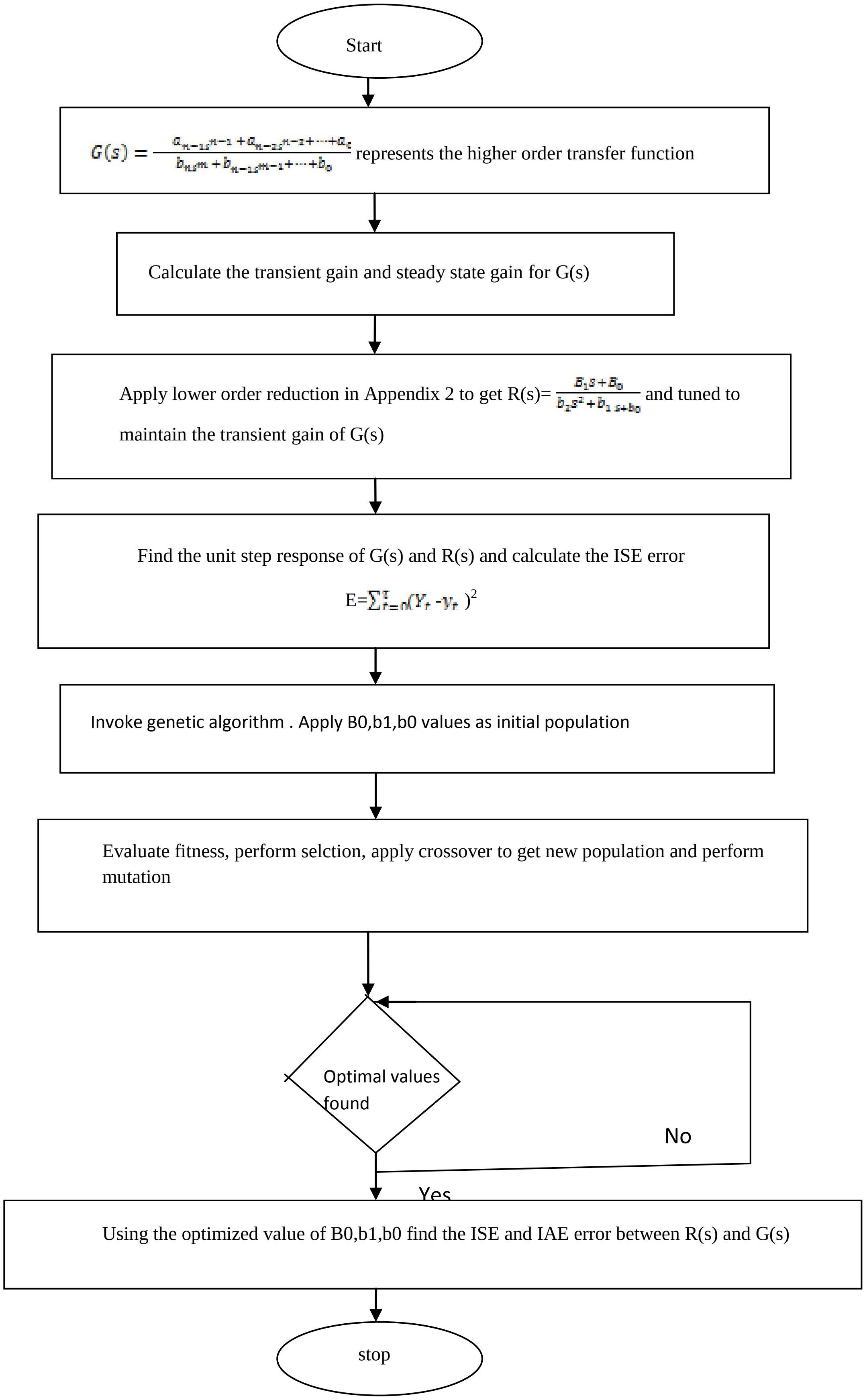

Fig2: Flowchart for Genetic Algorithm

Table 2: Reduced errors due to genetic algorithm in the evaluation of G13,G21,G31,G41

Reduced transfer function using genetic algorithm	B0	b1	b2	IAE using genetic algorithm	IAE using Algebraic method	ISE using genetic algorithm	ISE using Algebraic method
G13= $\frac{-1.1\,s+2.8705}{s^2-0.0922s+0.0339}$	2.8705	-0.0922	0.0339	**3.001e+004**	4.828e+004	**2.575e+008**	7.98e+008
G21= $\frac{-9207\,s+4.7874}{s^2+350.5581-0.3551}$	4.7874	350.5581	-0.3551	**8.718e+004**	2.868e+005	**8.634e+009**	1.157e+10
G31= $\frac{6563\,s+6.3912}{s^2+0.0581s+1.8084e-08}$	6.3912	0.0581	1.8084e -08	**8.57e+006**	9.128e+006	**2.442e+013**	2.166e+13
G41=$\frac{-8868\,s+2.3705}{s^2-0.2803s+0.0939}$	2.3705	-0.2803	0.0939	**1.399e+007**	1.437e+007	**7.782e+013**	8.005e+13

6. CONCLUSION

The development of low order transfer function models are required due to the difficulties encountered in the development of control strategies for the benchmark problem proposed by ALSTOM. In this direction, the authors have developed low order transfer function models using Algebraic method and reduced order approximation. The performance of these models has been evaluated on the basis of ISE and IAE error criteria. It is observed that the low order models derived using algebraic methods is much superior to one proposed by Haryanto et.al.Some lower order transfer functions obtained using algebraic method are found to have higher error than those obtained by RGA loop pairing method. Using Genetic Algorithm these errors are minimized and it is believed that the models proposed by algebraic method with Genetic Algorithm will become basis for further research on Gasifier control.

7. ACKNOWLEDGEMENTS

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APPENDIX 1

Transfer function matrix of ALSTOM plant using algebraic method

$$G11= \frac{-43.210273s^2-32.8849432314s+10.5403}{-0.0083690166s^2+0.067824414s+0.0019433}$$

$$G_{12}= \frac{0.67268851s^2+0.22784337s+1.36739}{8.7409426609s^2-6.32996277s-0.0002336}$$

$$G_{13}=\frac{-29.2949577767s^2+58.590928399s+0.99338}{0.9053252009s^2+0.217203375s-0.00002424}$$

$$G_{14}=\frac{11.42165811s^2-18.197458774s+2.892}{-298.17003810s^2+56.7756422s-2.2915}$$

$$G_{21}=\frac{0.769919483 5s^2-0.46212524 16s+1.4975}{-0.000053755 34s^2-0.0000999029s-3.530*10^{\wedge}-5}$$

$$G_{22}=\frac{0.11199621 25834s^2-0.33505277 8707s+1.5892}{-10.666078439387s^2-3.7028097164s-1.016069*10^{\wedge}-3}$$

$$G_{23}=\frac{-38.1754867787s^2-606.4765403s+1.03212}{-0.176233518s^2-0.067401899s+0.0004235}$$

$$G_{24}=\frac{7.589742045s^2+3.2012649 1848s+0.80506}{66.2192853528s^2+13.8974102235s+0.39192}$$

$$G_{31}=\frac{7.3194326 1016s^2-83.3609061793s+0.76028}{-0.011722633s^2-0.000526 1888s+2.49106*10^{\wedge}-5}$$

$$G_{32}=\frac{-8.34856920133s^2+15.2823278158s+1.4825}{26.0070991592s^2+2.5943768447s+0.000366}$$

$$G_{33}=\frac{-2.8969959854S^2-269.839875362S+1.645}{-0.1417932867S^2-0.0558268 2S+0.538723*10^{\wedge}-4}$$

$$G_{34}=\frac{-0.14942256 9149s^2+0.605489884s+0.8755}{-13.277800585s^2-15.07517 0803s-0.0538}$$

$$G_{41}=\frac{0.98989260 6658S^2-6.37153721233S+1.5006}{0.0005803934141S^2+0.0001311428155S-3.06317*10^{\wedge}-5}$$

$$G_{42}=\frac{0.86315233 8637S^2-1.69330243903S+2.3304}{-12.329066005S^2-3.02684037S-0.00315996}$$

$$G_{43}=\frac{-15.40091193 04S^2-2940.056236928S+2.31138}{-0.56675051 4100S^2-0.187456115 2S+0.0021771}$$

$$G_{44}=\frac{201.44236171406 88S^2+275.777196179 1S+0.81865}{-4192.3174269 68S^2-1162.912156389S-0.01737}$$

APPENDIX 2

Lower order Transfer function reduction:

Consider an n^{th} higher order system represented by its transfer function

$$G(s) = \frac{N(s)}{D(s)} = \frac{\sum_{i=0}^{n-1} A_i s^i}{\sum_{i=0}^{n} a_i s^i} = \frac{A_{n-1}s^{n-1}+A_{n-2}s^{n-2}+\cdots+A_2 s^2+A_1 s+A_0}{a_n s^n+a_{n-1}s^{n-1}+\cdots+a_2 s^2+a_1 s+a_0}$$

$$\text{First Order} = \frac{A_0}{a_1 s+a_0} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$\text{Second order} = \frac{A_1+A_0}{a_2 s^2+a_1 s+a_0} \ldots\ldots\ldots\ldots(2)$$

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$$\text{n-1 order} = \frac{A_{n-2}s^{n-2}+A_{n-3}s^{n-3}+\cdots+A_2 s^2+A_1 s+A_0}{a_{n-1}s^{n-1}+a_{n-2}s^{n-2}+\cdots+a_2 s^2+a_1 s+a_0} \text{-------------}(3)$$

Equations (1) through (3) gives the lower order model for higher order system G(s). For n higher order system, (n-1) lower order models can be formulated.