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Lower Order Modeling and Control of Alstom Fluidized Bed Gasifier

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Additional information is available at the end of the chapter

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1. Introduction

Integrated coal gasification combined cycle (IGCC) is a technology wherein coal is converted to fuel gas also referred as syngas or synthesis gas. Powdered coal is made to be in contact with a mixture of oxygen(or air) and steam to produce fuel gas. This fuel gas is burnt in a gas turbine coupled with generator to produce power. The waste heat from the gas turbine is used to produce steam and the steam is sent to a steam turbine for additional power generation (Ramezan and Stiegel, 2006).

Though, IGCC has a number of technical advantages, but until recently, its application has been limited due to its higher capital costs plus the availability of cheap natural gas. However, with pollution limits becoming more stringent and natural gas prices increasing, the performance of IGCC will become more attractive and its technical advancement will further reduce its cost.

Gasification is a technology that had its beginnings in the late 1700s. In the 19th century, gasification was widely used for the production of "town gas" especially for urban areas (Ramezan and Stiegel, 2006). But due to the widespread availability of natural gas, it got vanished in the 20th century. Today, the IGCC technology is being widely used throughout the world. 250MW IGCC demonstration plants are being constructed at Tianjin in china. In India, Andhra Pradesh Power Generation Corporation Ltd in association with Bharat heavy Electricals Limited proposed 125 MW IGCC plant at Vijayawada. In USA, 262 MW Wabash River IGCC power plants in Indiana (later acquired by Conoco Philips) and 250MW Tampa Electric Co. Polk Power Station IGCC in Florida (later acquired by GE Energy) are the two main commercial IGCC coal based power plants. Even though a number of IGCC projects exist, the UK's Clean Coal Power Generation Group, ALSTOM has undertaken a detailed study on the development of a small-scale prototype integrated plant (PIP), based on the air blown gasification cycle with 150 MW output (Pike *et al.*, 1998). This type of prototype plant

is useful in understanding the physics of the process, designing control systems for integrated operation.

2. Mathematical modelling

In general, mathematical modeling has been a useful tool for performance analysis, control system design, optimization and diagnosis of plants [Sivakumar and Ganapathiraman 2006]. The approach towards mathematical modeling depends upon the purpose for which the modeling is done. A detailed nonlinear mathematical model for a power boiler had been developed [Sivakumar and Bhattacharya 1979] using first principles approach – conservation of mass, energy and momentum to study the boiler transients for different types of disturbances. A furnace model with detailed calculations on the heat flux falling on different zones of furnace had been developed to study on the water wall tube failures [Sivakumar et.al 1980]. Low order transfer function models for power plant had been developed to study the performance of the proposed controllers and to design training simulators [Sivakumar et.al 1983]. This chapter deals with the development of low order mathematical models for ALSTOM gasifier which will be available to research community to study the efficiency of different control algorithms for specified disturbances. Further the suitability of conventional PID controllers for ALSTOM gasifier is investigated by the authors.

3. Air blown gasification cycle

ABGC is a hybrid combined cycle power generation technology. It was first conceived by British Coal Corporation (BCC) and developed in 1990s by Clean Coal Power Generation Group (CCPGG). Later the ABGC technology is purchased by Mitsui Babcock Energy Limited (Mitsui Babcock). Advanced design for this gasification is later done by the combined industrial collaborators - GEC Alsthom, Scottish Power plc and Mitsui Babcock with support from the European Commission's (EC's) THERMIE Programme and Department of Trade and Industry (DTI) (Pike *et al.*, 1998). Figure 1 shows the block diagram of ABGC.

Coal, steam and air react within the gasifier operating at 22bar pressure and 1150k temperature conditions in order to produce fuel gas with low calorific value. Limestone is also added in order to remove sulphur. This fuel gas is burnt in a gas turbine coupled with generator to produce electricity.

Approximately 20% of carbon in the coal does not react in gasifier which is extracted through ash removal system. This unburned carbon is fed to circulating fluidized bed combustor (CFBC) operating under atmospheric pressure and 1150k temperature conditions. Here the remaining unburned carbon is combusted completely. The water/steam (two phase mixture) absorbs heat from CFBC water walls. The steam separated by drum internals goes through different stages of super heaters receiving heat from exhaust gas coming from gas turbine (Pike *et al.*, 1998). The resulting high pressure steam is given to steam turbine coupled with generator to produce additional power generation. The total capacity of commercial ABGC is 525 MW approximately.
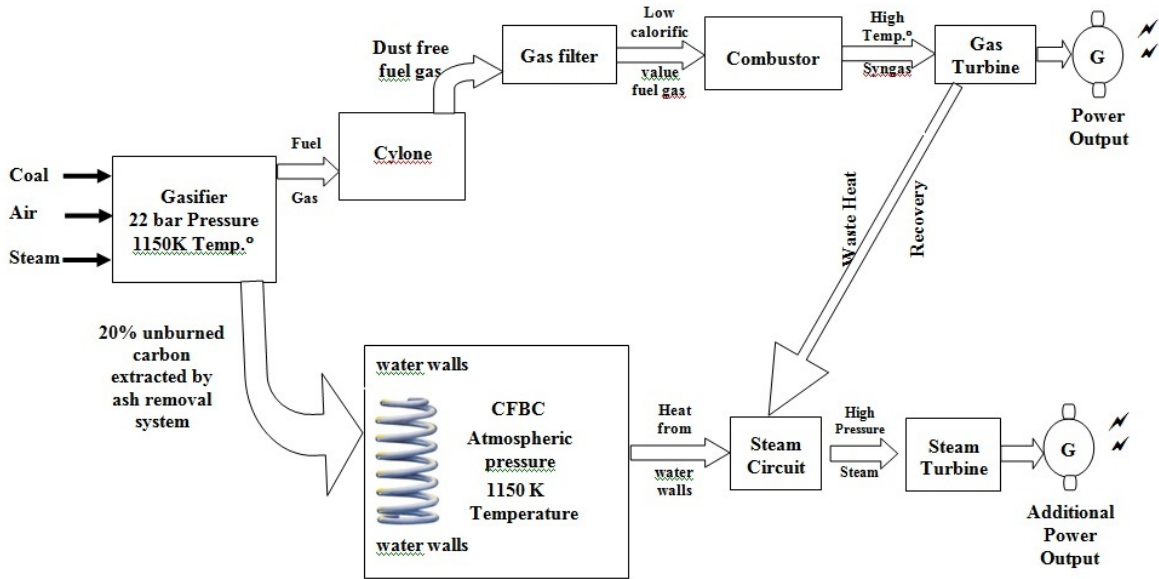
Figure 1. The Air Blown Gasification Cycle

4. Types of gasifier

There are three types of gasifier namely fixed bed, fluidized bed and entrained flow (Phillips, 2006).

4.1. Fixed bed gasifier

Here coal enters at the top of the reactor and air or oxygen enters at the bottom. As the coal moves slowly down the reactor, it is gasified and the remaining ash drops are collected at the bottom of the reactor. Example: British Gas Lurgi(BGL), Lurgi (Dry Ash) The figure 2 shows moving bed gasifier.
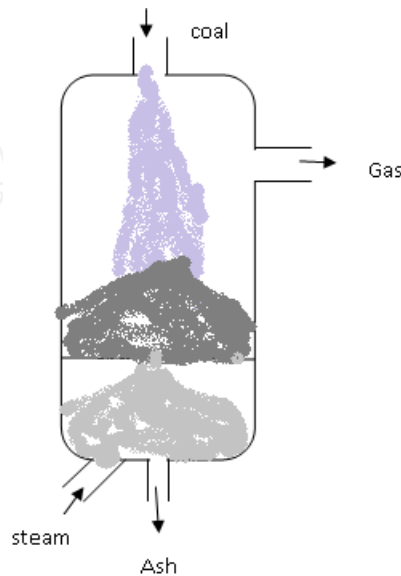

Figure 2. Moving bed gasifier

4.2. Entrained flow

Finely-ground coal is injected in co-current flow with the oxidant. The coal rapidly heats up and reacts with the oxidant. Gas is collected at the bottom. Most entrained flow gasifiers use oxygen rather than air. Example: GE entrained flow gasifier(Polk Station), E-Gas, Mitsubish Figure 3 shows entrained flow gasifier.
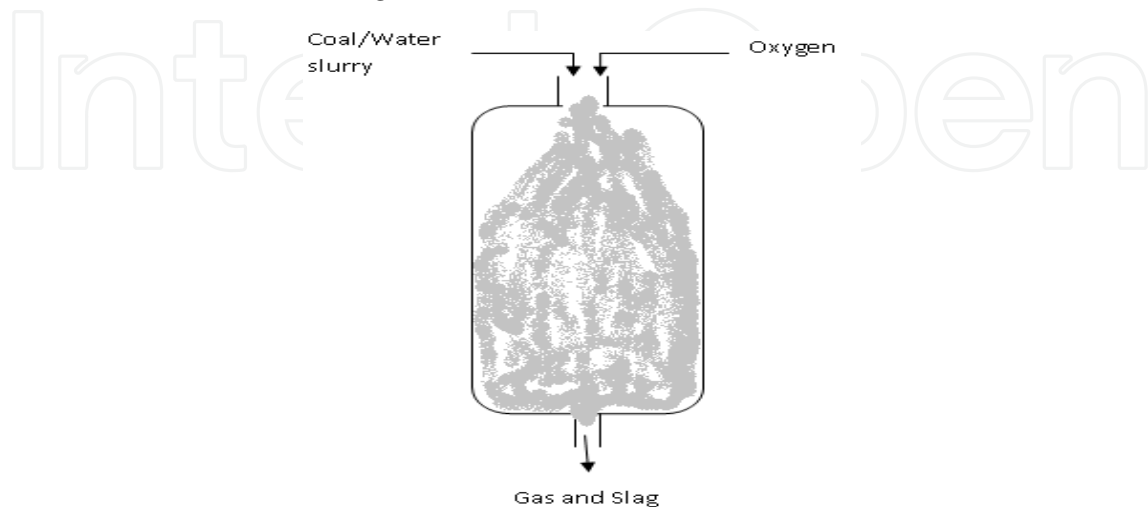

Figure 3. Entrained Flow Gasifier

4.3. Fluidized bed gasifier

A fluidized bed gasifier is a well-stirred reactor in which new coal particles is mixed with older, partially gasified and fully gasified particles. The mixing gives uniform temperatures throughout the bed. The flow of gas into the reactor (oxidant, steam, recycled syngas) must be sufficient to float the coal particles within the bed. However, as the particles are gasified, they will become smaller and lighter and will be entrained out of the reactor. Example: HT Winkler, KRW (Kellogg –Rust-Westinghouse) and ALSTOM gasifier.
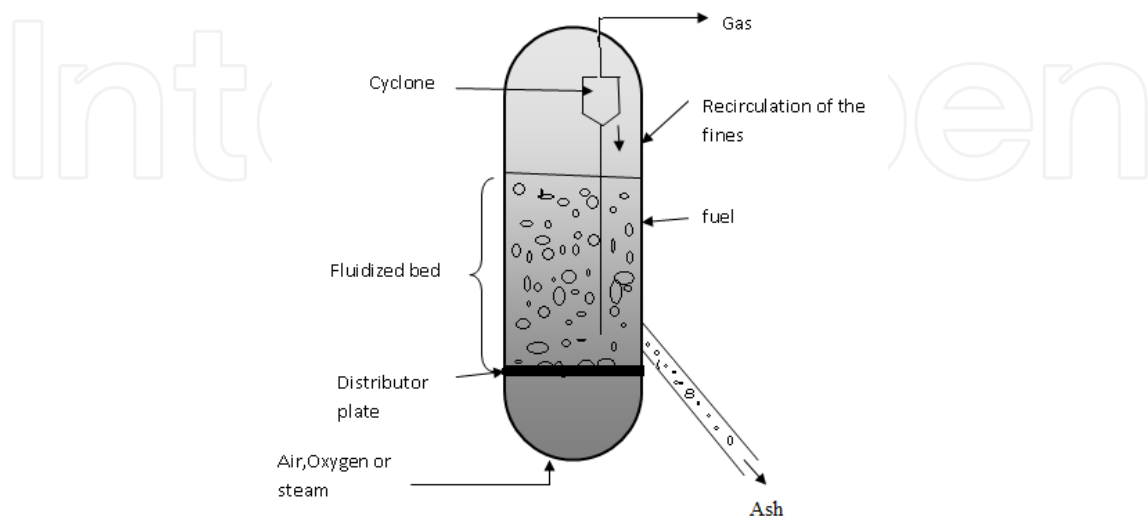

Figure 4. Fluidized bed gasifier

5. ALSTOM gasifier model

Gasifier model is the most complex one in coal gasification. It was first started by CRE Group Ltd in 1992. Later it was continued at GEC ALSTHOM mechanical Engineering Centre. The incoming coal is dried and de-volatilized to yield char, ash and volatile gases. The oxygen in fluidized air reacts with carbon in the char to form carbon monoxide and carbon dioxide. Both exothermic and endothermic reactions occur simultaneously in the gasifier. The main equations in gasifier are

$$C + O_2 \rightarrow CO_2 \qquad (1)$$

$$C + {}^{1}\!/_2\, O2 \rightarrow CO \qquad (2)$$
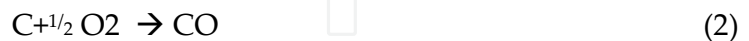
Equation 1 and 2 are exothermic gasification.

The carbon-dioxide reacts more with carbon to form carbon-monoxide. Also steam reacts with carbon to form carbon-monoxide and hydrogen.

$$C + CO_2 \rightarrow 2CO \qquad (3)$$

$$C + H_2O \rightarrow CO + H_2 \qquad (4)$$

Equation 3 and 4 are endothermic reactions.

The un-reacted char is added to the bed which is maintained at a constant height by char extraction system.

5.1. Alstom gasifier: Input and output variables

Alstom gasifier represents a difficult process for control because of its multivariable and non-linearity in nature with significant cross coupling between the input and output variables (Dixon 2004).

The controllable input variables to the gasifier are

- Char off-take (u1)   WCHR(kg/s)
- Air flow rate(u2)   WAIR(kg/s)
- Coal flow rate(u3)   WCOL (kg/s)
- Steam flow rate(u4)   WSTM(kg/s)
- limestone flow rate (u5)   WLS(kg/s)

The Controlled output variables are:

- Gas calorific value (y1)   CVGAS(J/kg)
- Bed mass (y2)   MASS(kg)
- Fuel gas pressure (y3)   PGAS(N/m²)
- Fuel gas temperature (y4)   TGAS(K)

One of the inputs, limestone mass (WLS) is used to absorb sulphur in the coal and its flow rate is set to a fixed ratio of 1:10 against another input coal flow rate.(WCOL).This leaves

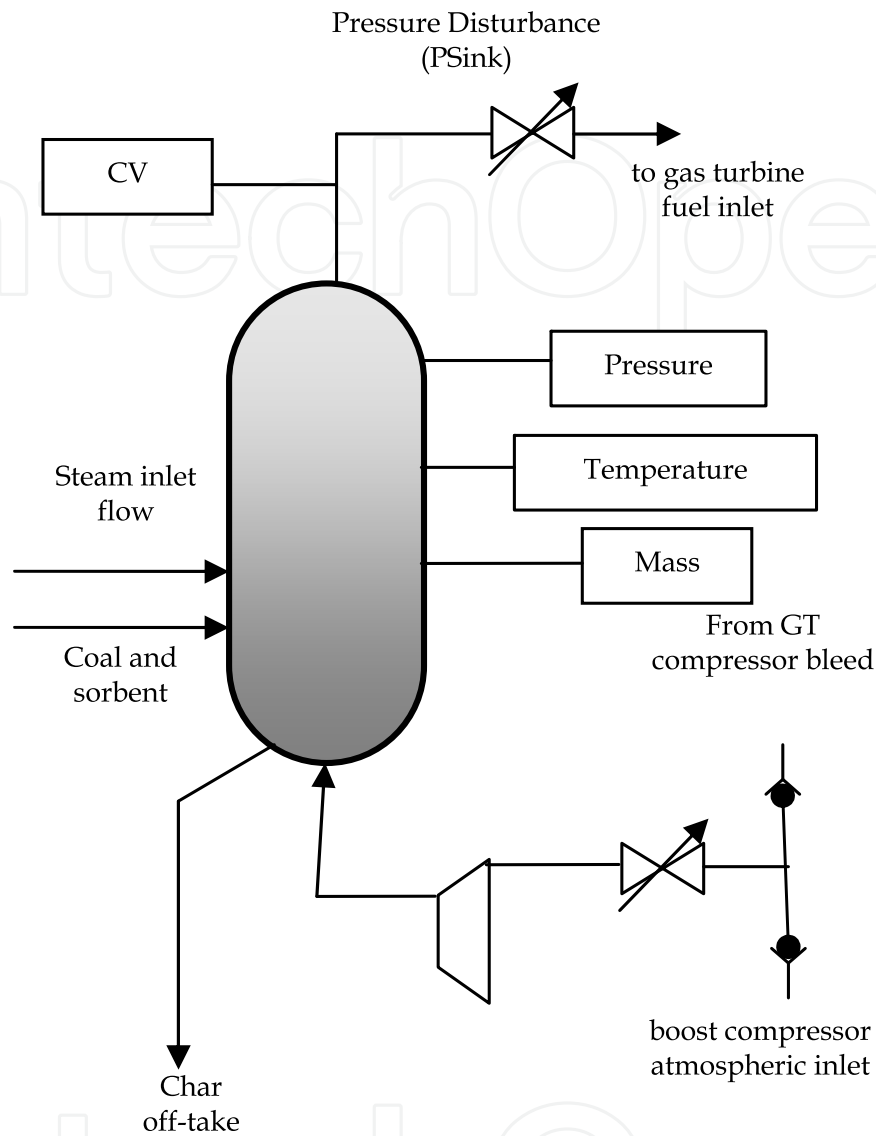effectively 4 degrees of freedom for the control design. Fig 5 shows gasifier with input and output variables.

Figure 5. Gasifier with input and output variables

5.2. Load demand on gasifier

The flow rate of syngas to gas turbine is controlled through a valve at the inlet of turbine (also referred as controlled input disturbance to the gasifier). The pressure at the inlet of turbine called as PSink is the controlled variable. The control problem is to study the transient behavior of gasifier process variables such as pressure, temperature of the syngas for typical variations in gas flow drawing rate to gas turbine through appropriate changes in the throttle valve. Any proposed control system should control the pressure and temperature of the syngas at the inlet of gas turbine for any variation in gas turbine load – which in turn will affect throttle valve moment-without undue overshoots and undershoots. In fact this particular aspect has been posed as a control challenge problem for gasifier by ALSTOM.

6. ALSTOM benchmark challenges

The demand for clean air and stringent environmental regulations are forcing us to look for an alternate technology with reduced pollution emission and higher power generation. As a result of this, IGCC power plants are being developed all over the world. ALSTOM small-scale prototype (PIP) based on air-blown gasification cycle is one such IGCC. One of the component in ABGC called gasifier, is difficult to be controlled. For this reason, ALSTOM Power technology center issued a bench mark challenge to research community

- To come out /propose a suitable control strategy/algorithms so as to have an efficient control of pressure and temperature of syngas without having an undue overshoot and undershoot values equal or less than those specified in the constraints by ALSTOM for specified load disturbance through the throttle value for different operating loads such as 100%, 50%and no-load.

The ALSTOM gasifier is modeled in state space form 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

Towards this purpose, ALSTOM has made it available the following :

- A, B, C, D, x(0), Y for three different loads- 100%, 50% and no-load.

A virtual gasifier mathematical model is made available with the above quantities **(http://www.ieee.org/OnComms/PN/controlauto/benchmark.cfm.)** and researches can attempt different control philosophies to meet the challenge posed by ALSTOM.

The input and output variables, allowable limits on output variables during load transients for three different loads (100%, 50% and no-load) as given by ALSTOM are reproduced in Tables 1 and 2 for ready reference.

6.1. Input and output constraints

The plant inputs and outputs with their limits are given in Tables 1 and 2 respectively (Seyab *et al.*, 2006)

Inputs	Description	Maximum Value	Rate	Steady state values		
				100%	50%	0%
WCHR(kg/s)	Char extraction flow rate	3.5	0.2 kg/s^2	0.9	0.89	0.5
WAIR (kg/s)	Air flow rate	20	1.0 kg/s^2	17.42	10.89	4.34
WCOL(kg/s)	Coal flow rate	10	0.2kg/s^2	8.55	5.34	2.136
WSTM(kg/s)	Steam flow rate	6.0	1.0kg/s^2	2.70	1.69	0.676
WLS(kg/s)	Limestone flow rate	1.0	0.02kg/s^2	0.85	0.53	0.21

Table 1. Input Variables and Limits

Outputs	Description	Allowed fluctuations	Steady state values		
			100%	50%	0%
CVGAS(MJ/kg)	Fuel gas calorific value	± 0.01	4.36	4.49	4.71
MASS(kg)	Bedmass	± 500	10000	10000	10000
PGAS(N/m^2)	Fuel gas pressure	$\pm 1 \times 10^4$	2×10^6	1.55×10^6	1.12×10^6
TGAS(K)	Fuel gas temperature	± 1.0	1223.2	1181.1	1115.1

Table 2. Output variables and limits

6.2. Researchers attempt in the first phase (1997-2001)

The first round challenge was issued in the year 1997. It included three linear models operating under 0%, 50% and 100% load conditions respectively. The model includes state space equation with A,B,C and D values. The challenge requires a controller which controls the gasifier at three load conditions with input and output constraints in the presence of step and sinusoidal disturbances. Many controllers have been suggested for the first challenge (Dixon, 1999).

1. Dixon (1999) used multivariable P and I controllers using multi-objective optimal tuning technique and model based predictive control design to meet the constraints.
2. Rice et al. (2000) proposed predictive control that uses linear quadratic optimal inner loop and it is supervised by an outer predictive controller loop.
3. Proportional integral plus (PIP) by Taylor et al. (2000) from Lancaster University was based on discrete time model of the plant.
4. Prempain et al. (2000) demonstrated the use of loop shaping H-infinity control design method.
5. The multi-objective Genetic algorithm (MOGA) was proposed by Griffin et al. (2000) which performed a loop-shaping H-infinity design.
6. A sliding mode, nonlinear design approach was suggested by Sarah Spurgeon. Here switching surface is designed to move the plant from one operating point to the other.

7. Neil Munrom decomposed the original problem into a series of much simpler schemes in an effort to divide and conquer rule.
8. Munro (2000) combined sequential loop closing with a high –frequency decoupling approach along with divide and conquer method

But none of the controller met all the objectives specified in the challenge – more so with particular reference to the transient limits imposed on output variables during load variations.

6.3. Second challenge

The second round challenge was issued in the year 2002. In the second round challenge, ALSTOM specified nonlinear simulation model in MATLAB/SIMULINK [10] and desired the controller capability during load changes and coal quality disturbance. Recently, a group of control solutions for the benchmark problem were presented at Control-2004 Conference at Bath University, UK in September 2004. Most of controllers were reported as capable of controlling the system at disturbance tests.

The author, Dixon (2002) used multi-loop PI controller to the gasifier control. He used system identification technique to obtain the linear model from the non – linear plant data. The base line controller was used by the other researchers for comparison purposes. The following controllers were suggested to meet the performance criteria (Dixon, 2004).

1. Multi objective optimization approach suggested by Anthony Simms from Nottingham University needs further improvement by the addition of proportional control loops.
2. H-infinity design approach given by Sarah Gatley from Leicester University used loop shaping combined with anti-windup compensator. It produced a robust design because of its simple design process and without the need for detailed knowledge of the plant.
3. Multiple PID controller design using penalty based multi objective genetic algorithms by Adel Farag from Technical University of Hamburg gave excellent results that satisfied reasonable input output constraints.
4. A novel controller by Tony Wilson from Nottingham University used state estimators to improve on the base line performance. Kalman filters are used to estimate the pressure disturbance and coal quality change.
5. Proportional integral plus controller by James Taylor of Lancaster University used discrete time linear model of the gasifier.
6. Model Predictive controller using a linear state space model of the plant was a collaborative effort from Cranfield and Loughborough.

All the papers had achieved reasonable success in terms controlling the gasifier model. But none of the controller met the overall performance criteria and still this benchmark challenge is left for the academicians for further research.

The difficulty in meeting the performance criteria appears to necessarily work with the higher order model for control system design. This motivates the authors to derive low order transfer function models for control system study.

7. Low 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 (Dixon 2004). It necessitates low order model for further control research. 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:

$$\begin{bmatrix} y1(s) \\ y2(s) \\ y3(s) \\ y4(s) \end{bmatrix} = \begin{bmatrix} G11(s) & G12(s) & G13(s) & G14(s) \\ G21(s) & G22(s) & G23(s) & G24(s) \\ G31(s) & G32(s) & G33(s) & G34(s) \\ G41(s) & G42(s) & G43(s) & G44(s) \end{bmatrix} \begin{bmatrix} u1(s) \\ u2(s) \\ u3(s) \\ u4(s) \end{bmatrix} + \begin{bmatrix} Gd1(s) \\ Gd2(s) \\ Gd3(s) \\ Gd4(s) \end{bmatrix} P_{SINK}$$

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}
Gdi(s) = describing the impact of variation in Psink on output variable; i= {1,4}
Psink = sink gas pressure at gas turbine inlet.

It is to be noted that the denominator polynomial of each element G$_{ij}$ is of 24th order while the numerator is of order less than or equal to 23rd. A typical transfer characteristic between an output (pressure) due to all inputs shown diagrammatically as follows:
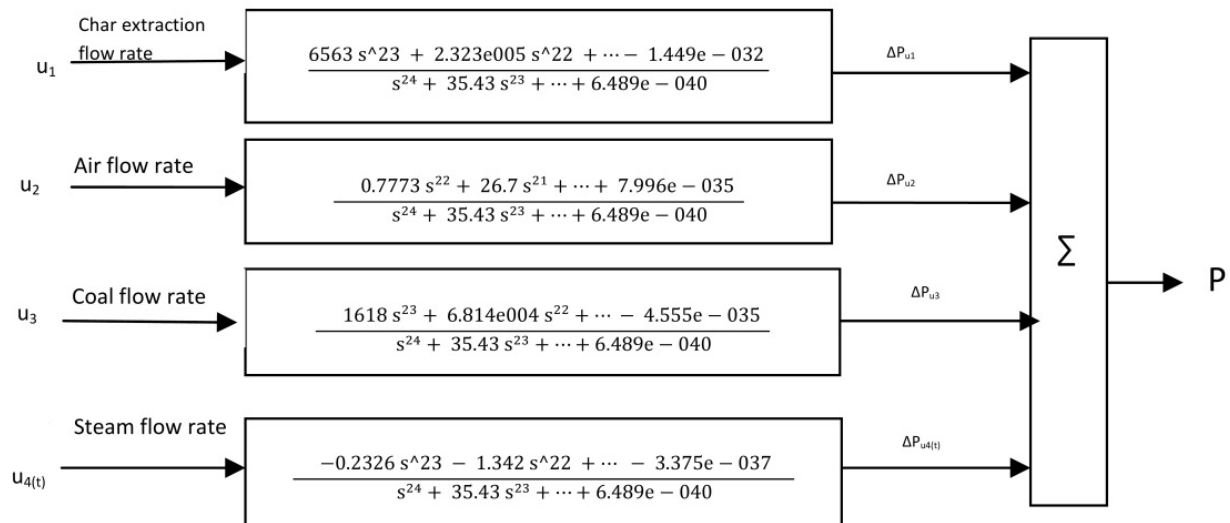

Figure 6. Transfer characteristic between pressure due to all inputs

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

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

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 different methods.

It is observed that author Haryanto et al. (2009) developed an equivalent lower order transfer function models towards the development of integrated plant simulator. In this chapter, the authors have developed lower order transfer function models using algebraic and reduced order approximation methods (Sivakumar and Anithamary, 2011).

7.1. Reduced order approximation (RSYS)

The matlab command RSYS = BALRED(SYS,ORDERS) computes a reduced order approximation(RSYS) of LTI system. The desired order (number of states) is specified by ORDERS. BALRED uses implicit balancing techniques to compute the reduced-order approximation RSYS. The second order transfer function is obtained using Henkel Singularity approximation method. The transfer function for typical block G11 corresponding to 100% load is given below:

$$G11 = \frac{-1.197e004\ s^2 + 330.4\ s + 0.001125}{s^2 + 0.0008608\ s + 2.075e-007}$$

All the transfer function blocks G_{ij} :   (i = {1,4}, j={1,4}) evaluated using reduced order approximation by the authors corresponding to 100%, 50% and no-load are given in Appendix A, Appendix B and Appendix C.

7.2. Algebraic method

The higher order transfer function is equated with the lower order model:

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

On cross multiplying, the equation becomes

$$(a_{n-1s^{n-1}} + a_{n-2s^{n-2}} + \cdots + a_0)(B_{2S^2} + B_1 s + B_0)$$
$$= (b_{ns^m} + b_{n-1s^{m-1}} + \cdots + b_0)(A_{2S^2} + A_1 s + A_0)$$

The ALSTOM transfer function for G_{11} is given below

$$G11 = \frac{\begin{array}{c} 0.03215 s^{22} + 14.45 s^{21} + 1289 s^{20} + 1467 s^{19} + 721.8 s^{18} + 208.5 s^{17} + \\ 40.02 s^{16} + 5.452 s^{15} + 0.547 s^{14} + 0.04129 s^{13} + 0.002367 s^{12} \\ + 0.0001031 s^{11} + 3.388e-006 s^{10} + 8.235e-008 s^9 + 1.435e-009 s^8 \\ 1.695e-011 s^7 + 1.246e-013 s^6 + 4.869e-016 s^5 + 8.221e-019 s^4 \\ + 6.532e-022 s^3 + 2.442e-025 s^2 + 3.437e-029\ s + 1.126e-034 \end{array}}{\begin{array}{c} s^{24} + 35.38 s^{23} + 78.31 s^{22} + 68.51 s^{21} + 32.81 s^{20} + 9.998 s^{19} + 2.106 s^{18} + \\ 0.3225 s^{17} + 0.03703 s^{16} + 0.00325 s^{15} + 0.0002203 s^{14} + 1.156e-005 s^{13} \\ 4.687e-007 s^{12} + 1.45e-008 s^{11} + 3.36e-010 s^{10} + 5.64e-012 s^9 \\ 6.52e-014 s^8 + 4.785e-016 s^7 + 1.95e-18 s^6 + 3.99e-021 s^5 + \\ 4.505e-024 s^4 + 2.982e-024 s^3 + 1.148e-030 s^2 + 2.389e-034 s + \\ 2.078e-038 \end{array}}$$

The a_0 can be obtained by the formula (Poongodi $et\ al.$, 2009)

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

$$a_0 = \frac{35.38/1 \pm 14.45/0.03215}{24 \pm 22}$$

a_0 = 10.5403, 242.4178, -9.0014, -207.0325

Taking the 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,

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

Similarly lower order models G12 to G44 corresponding to higher order models specified by ALSTOM can be obtained.

All the transfer function blocks Gij : (i = {1,4},j={1,4}) evaluated using algebraic method by the authors corresponding to 100%, 50% and no-load are given in Appendix A, Appendix B and Appendix C.

In order to evaluate the reduced order transfer function models obtained through different methods, the unit step response of ALSTOM model has been taken as reference response and the responses obtained through different methods as in figure 7 are compared and shown in figures 8-11 for typical transfer function blocks namely

G11 – the transfer characteristic between change in calorific value due to change in char extraction flow rate.

G24 – the transfer characteristic between change in temperature due to change in air flow rate.

G33 – the transfer characteristic between change in pressure due to change in coal flow rate.

G42 – the transfer characteristic between change in bedmass due to change in steam flow rate.
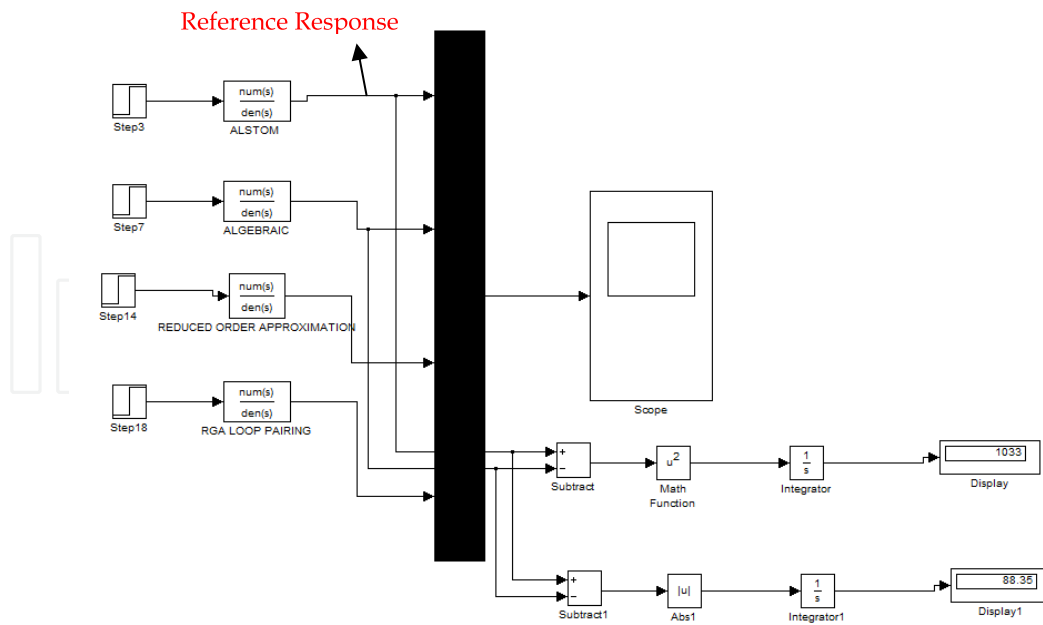
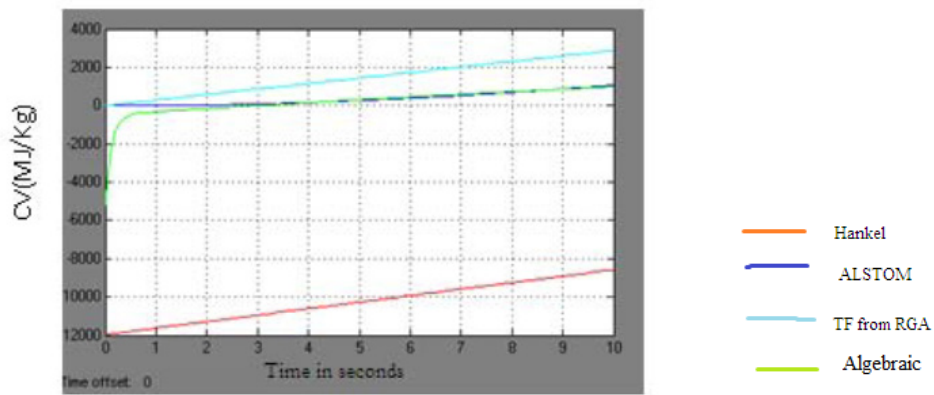**Figure 7.** Matlab SIMULINK model to evaluate the IAE and ISE error

Figure 8. Variation of calorific value(y1) with char extraction flow rate (u1) keeping u2,u3,u4 constant
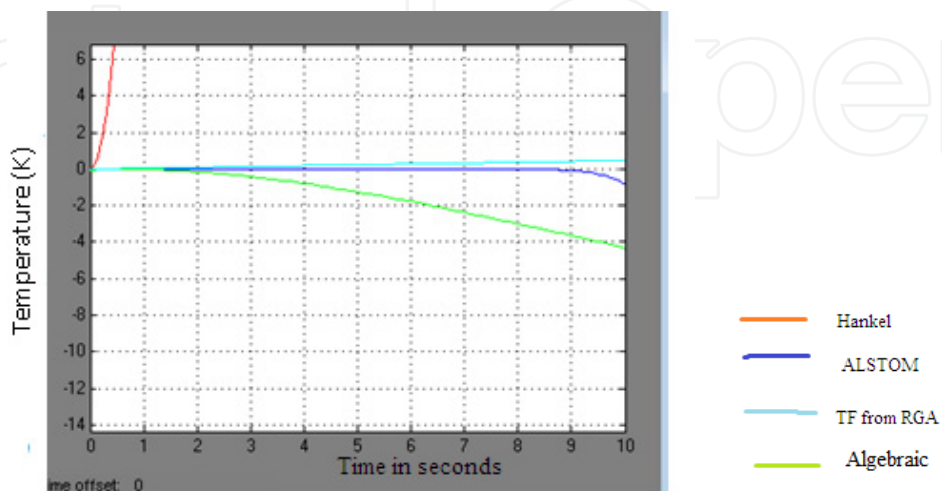

Figure 9. Variation of fuel gas temperature(y4) with air flow rate (u2) keeping u1,u3,u4 constant
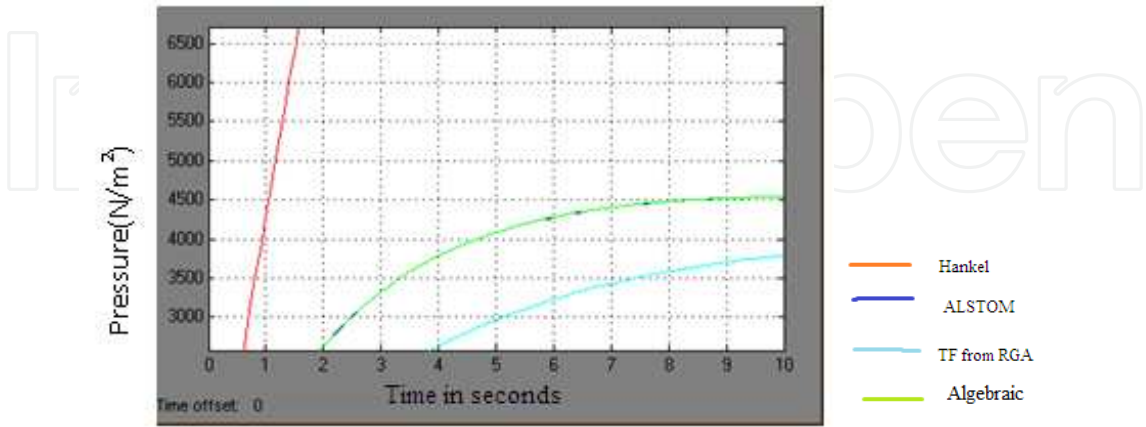
Figure 10. Variation of fuel gas pressure(y3) with coal flow rate (u3) keeping u1,u2,u4 constant

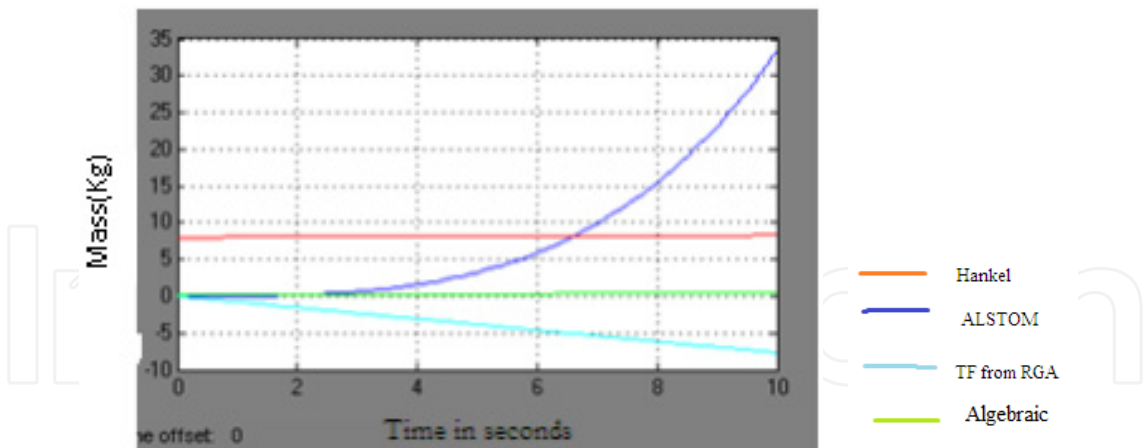**Figure 11.** Variation of Bed mass(y2) with change in steam flow rate (u4) keeping u1,u2,u3 constant

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, reduced order approximation and RGA loop pairing over a period of time (little above the rise time) are shown in Table 3 for 100% load.

Transfer function	INTEGRAL ABSOLUTE ERROR			INTEGRAL SQUARED ERROR		
	Algebraic method	Reduced order approximation	TF using RGA loop pairing	Algebraic method	Reduced order approximation	TF using RGA loop pairing
G11	1644	1.062e+005	1.087e+004	2.16e+006	1.133e+009	1.455e+007
G12	7.09	751.5	2.954e+005	7.606	1.013e+005	1.12e+010
G13	4.828e+004	4.48e+004	8.039e+004	7.98e+008	7.98e+008	7.784e+008
G14	5.096	88.35	2.308e+005	5.85	1033	6.955e+009
G21	2.868e+005	5.23e+006	8.71e+004	1.157e+10	3.598e+12	8.637e+009
G22	11.5	1.19e+004	20.97	20.74	2.549e+007	57.78
G23	50.56	4.638e+004	6.8e+004	1018	2.668e+008	5.145e+008
G24	73.09	76.29	114.2	1412	830.3	2555
G31	9.128e+006	6.606e+006	8.799e+006	2.166e+13	1.009e+13	2.519e+013
G32	0.4021	1747	6.277e+004	0.0362	3.051e+005	4.58e+008
G33	35.04	1.78e+005	9250	283.1	4.443e+009	9.1e+006
G34	2.549	141.8	1.086e+005	0.8598	3622	1.344e+009
G41	1.437e+007	2.407e+007	1.434e+007	8.005e+13	1.411e+014	7.98e+013
G42	15.18	1.103e+004	2.695	39.14	0.1632	1.213
G43	462.3	5.714e+004	1.133e+005	3.812e+004	5.035e+008	1.46e+009
G44	1.683	508.8	0.4994	0.3358	4.662 e+004	0.1532

Table 3. Integral Absolute and Squared error criteria for 3 models

It is observed that the low order models derived using algebraic methods is much superior to one proposed by Haryanto et.al., using RGA loop pairing and reduced order approximation proposed by authors.

7.3. Lower order modeling using genetic algorithm

Out of 16 transfer functions using algebraic method, four transfer functions G21, G31, G41 and G13 (shown in bold) are found to have higher ISE and IAE error criterion than the lower order models obtained using RGA loop pairing. This observation has motivated the authors to obtain further reduced order transfer function models with minimum ISE and IAE error criterion using genetic algorithm. Appendix D gives the auxiliary scheme for low order model (Sivanandam and Deepa, 2009).

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

$$G13=\frac{\begin{array}{c}-1.1s^{23}-12.44s^{22}+2893s^{21}+2764s^{20}+1212s^{19}+324.2s^{18}+59.29s^{17}+\\7.864s^{16}+0.7827s^{15}+0.05961s^{14}+0.003508s^{13}+0.00016s^{12}\\+5.623e-006s^{11}+1.505e-007s^{10}+3e-009s^{9}+4.293e-011s^{8}\\4.155e-013s^{7}+2.4446e-015s^{6}+6.972e-018s^{5}+4.046e-021s^{4}\\+8.036e-024s^{3}-.1.1772e-026s^{2}-5.48e-030\ s+8.511e-034\end{array}}{\begin{array}{c}s^{24}+35.38s^{23}+78.31s^{22}+68.51s^{21}+32.81s^{20}+9.998s^{19}+2.106s^{18}+\\0.3225s^{17}+0.03703s^{16}+0.00325s^{15}+0.0002203s^{14}+1.156e-005s^{13}\\4.687e-007s^{12}+1.45e-008s^{11}+3.36e-010s^{10}+5.64e-012s^{9}\\6.52e-014s^{8}+4.785e-016s^{7}+1.95e-18s^{6}+3.99e-021s^{5}+\\4.505e-024s^{4}+2.982e-024s^{3}+1.148e-030s^{2}+2.389e-034s+\\2.078e-038\end{array}}$$

The second approximation is given as

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

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 E is used to find R(s) from G(s)

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

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

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

$$=\frac{B_1s+B_0}{b_2s^2+b_1s+b_0}$$

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, Y_t is the unit step time response of the higher order system at the tth instant in the time interval $0\le t\le\tau$, where τ is to be chosen and y_t is the unit step time response of the lower order system at the tth 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 4 shows the IAE and ISE error using genetic algorithm is further reduced than using algebraic method. Figure 12 shows the flowchart for lower order modeling using Genetic Algorithm.

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
$G13 = \dfrac{-1.1\,s + 2.8705}{s^2 - 0.0922s + 0.0339}$	2.8705	-0.0922	0.0339	**3.001e+004**	4.828e+004	**2.575e+008**	7.98e+008
$G21 = \dfrac{-9207\,s + 4.7874}{s^2 + 350.5581 - 0.3551}$	4.7874	350.5581	-0.3551	**8.718e+004**	2.868e+005	**8.634e+009**	1.157e+10
$G31 = \dfrac{6563\,s + 6.3912}{s^2 + 0.0581s + 1.8084e-08}$	6.3912	0.0581	1.8084e-08	**8.57e+006**	9.128e+006	**2.442e+013**	2.166e+13
$G41 = \dfrac{-8868\,s + 2.3705}{s^2 - 0.2803s + 0.0939}$	2.3705	-0.2803	0.0939	**1.399e+007**	1.437e+007	**7.782e+013**	8.005e+13

Table 4. Reduced errors due to genetic algorithm in the evaluation of G13,G21,G31,G41
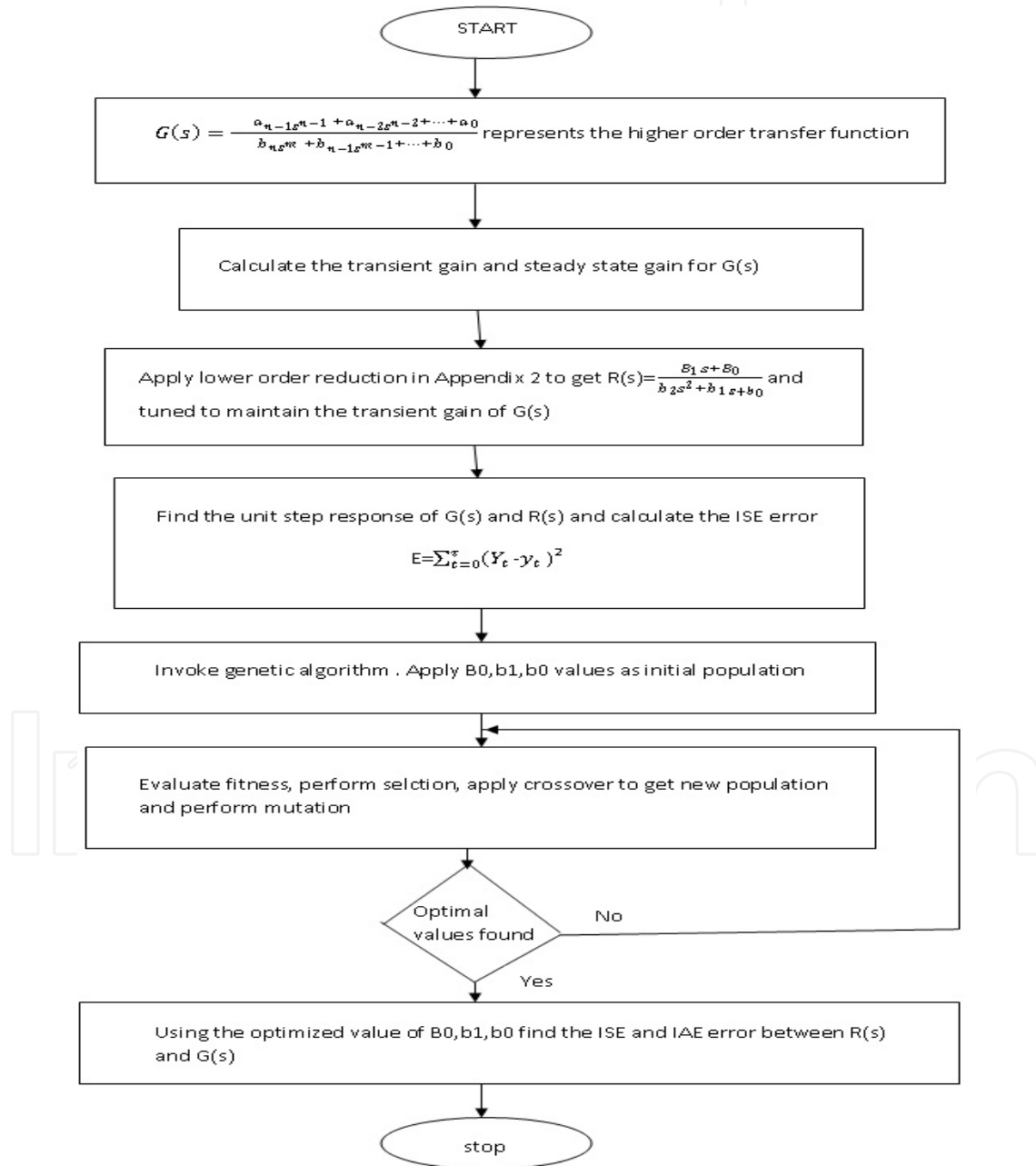

Figure 12. Flowchart for lower order modeling using Genetic Algorithm

Transfer function obtained using Genetic Algorithm seems to be the most effective method for obtaining lower order models. Though the transfer functions for G11, G31,G41, G22 have been obtained through genetic algorithm to illustrate the superiority over other methods, all the transfer function blocks can be obtained in the same way as explained earlier.

8. Gasifier control and simulation

Even though many advanced control algorithms are proposed for complex process and systems, the authors are strongly of the opinion that PID control will also meet the control requirements using appropriate controller constants and feed forwards if necessary. Hence the PID controller is considered as a tool for gasifier control and simulation studies are done.
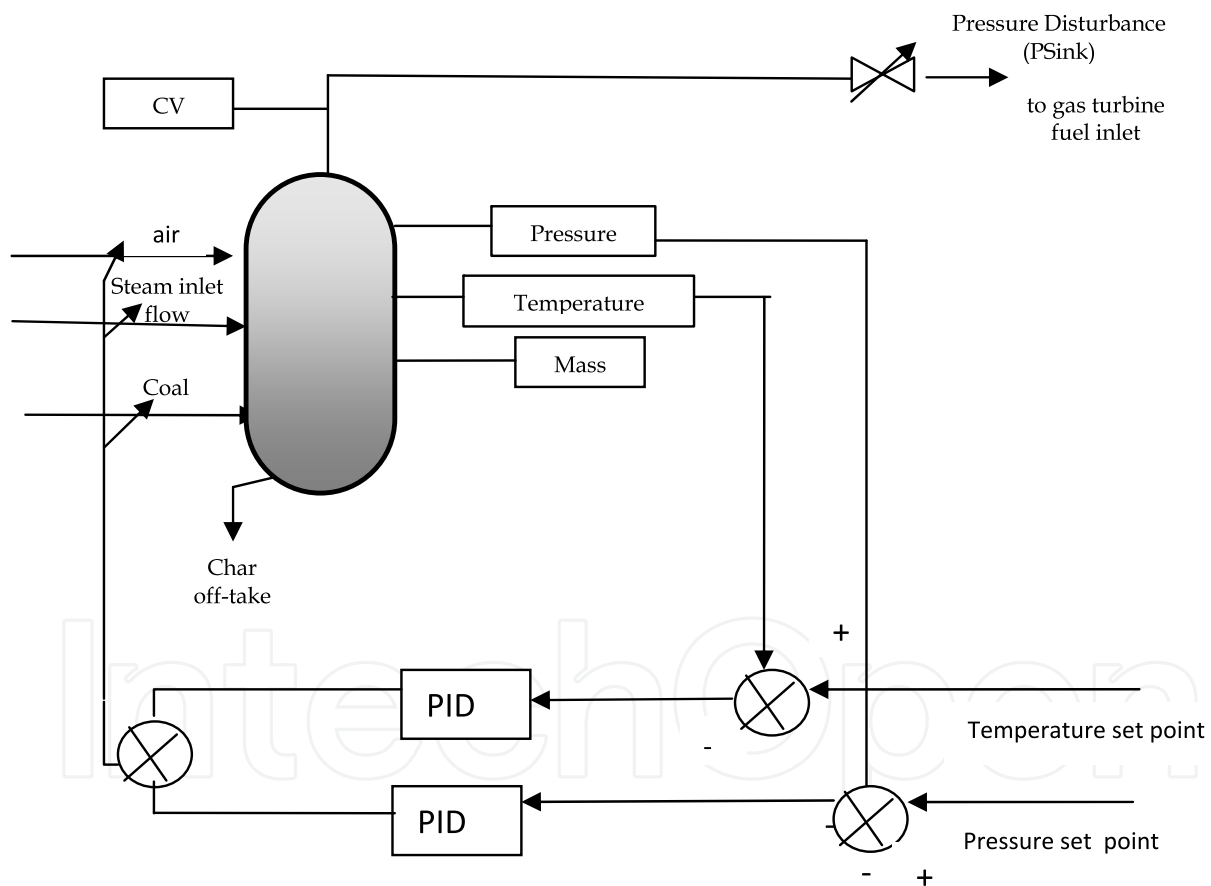

Figure 13. PID controller for pressure and temperature output variables

Here PID controller is used to vary the steam and coal inputs for syngas pressure and coal and air is varied for syngas temperature. Table 5 gives the PID parameters for pressure and temperature of the syngas

P-Psink error	Kp	Ki	Kd
PID(temperature)	0.5	0.25	0.001
PID (pressure)	7.5	4	3

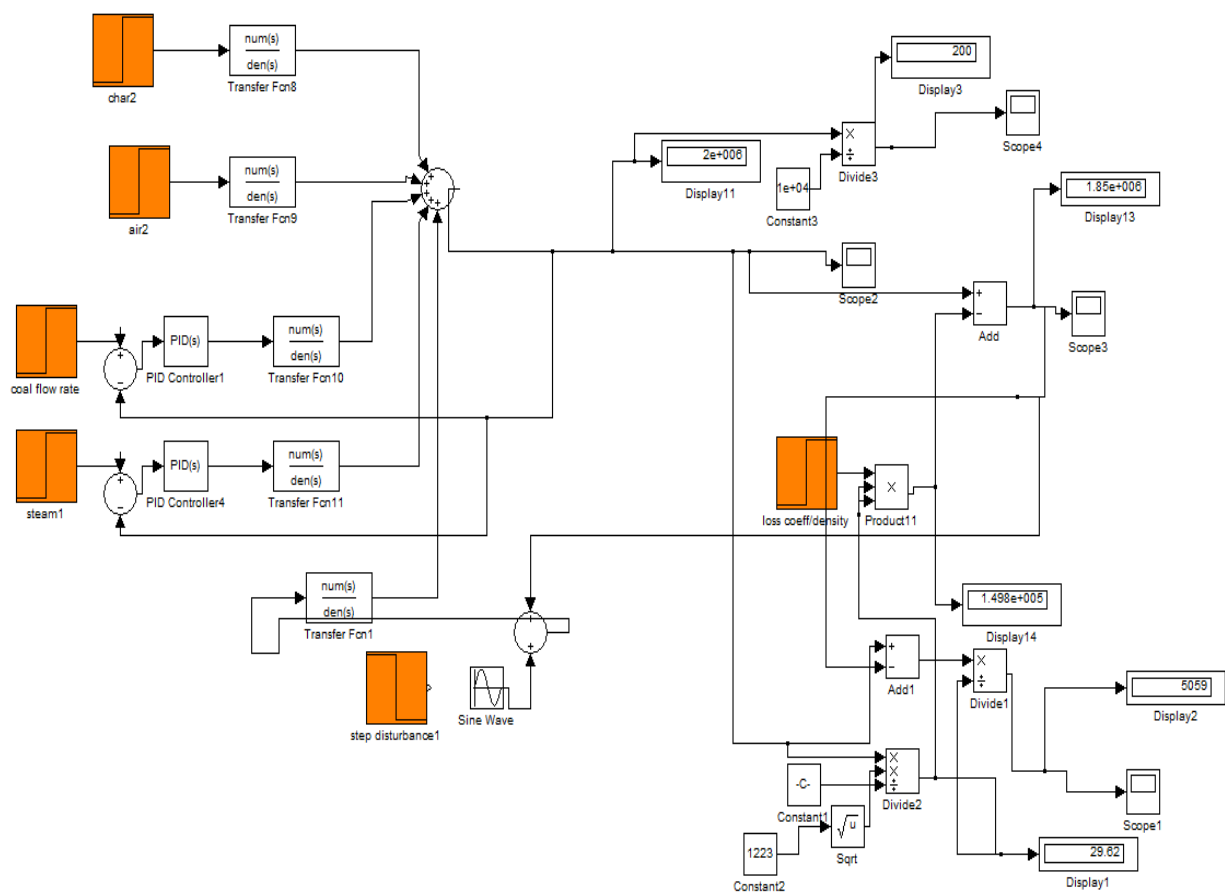**Table 5.** PID constants for syngas temperature and pressure

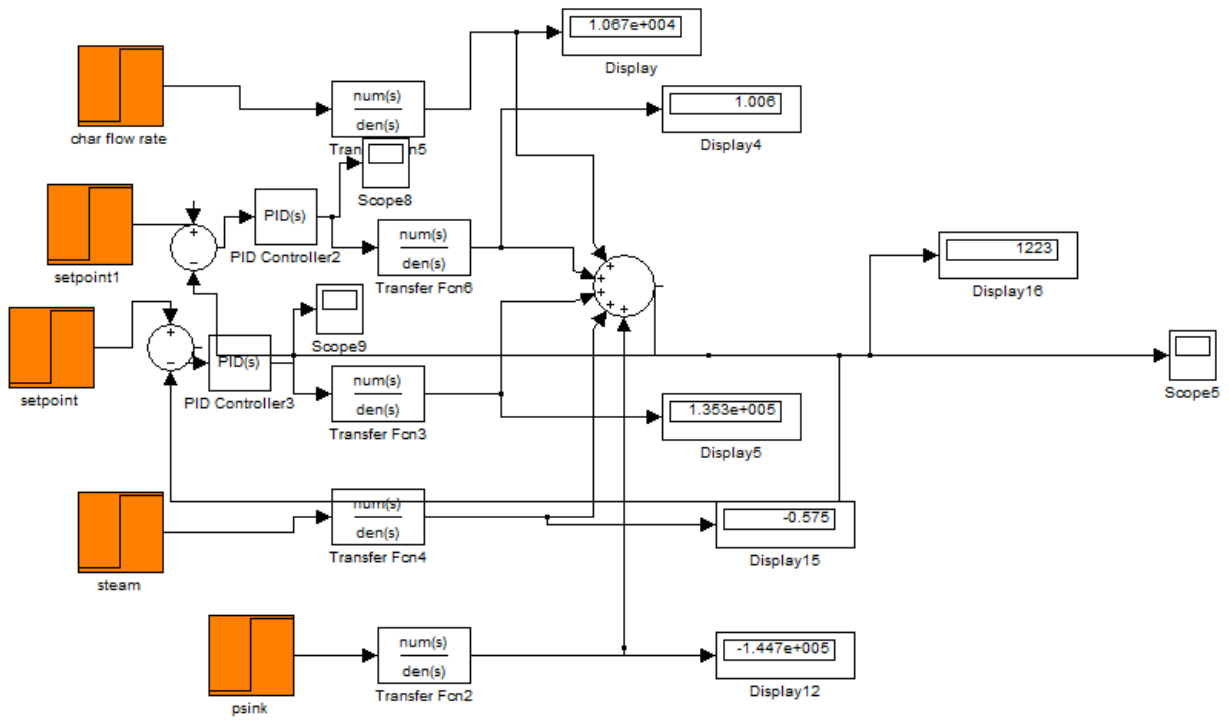**Figure 14.** SIMULINK model for syngas pressure in the presence of step and sinusoidal disturbances

Figure 15. SIMULINK model for syngas temperature in the presence of step and sinusoidal disturbances
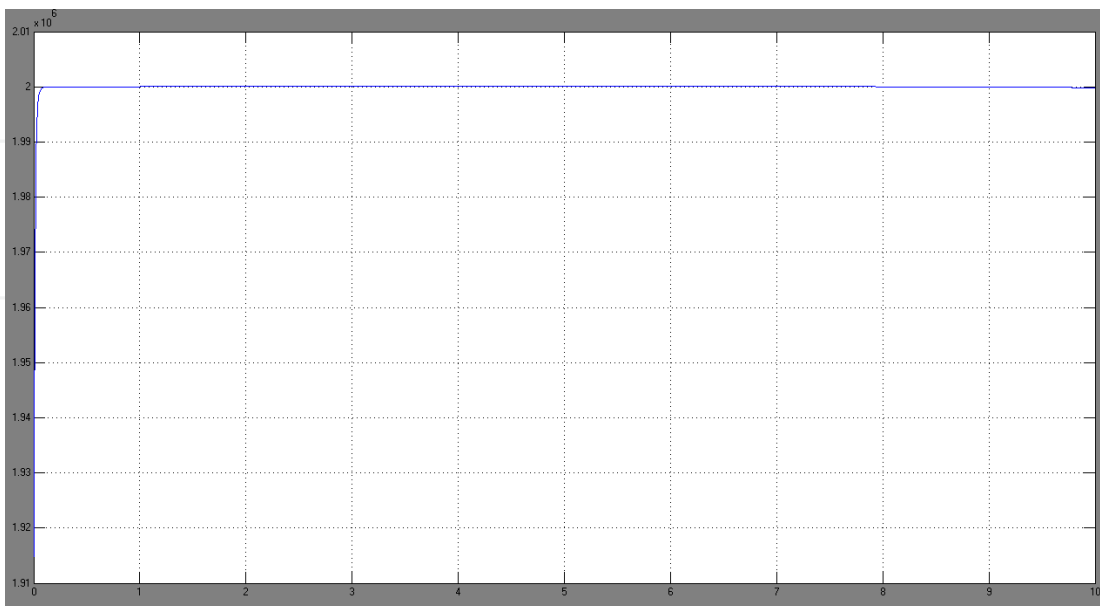

Figure 16. Syngas pressure maintaining at 2*10⁶N/m² in the presence of disturbance
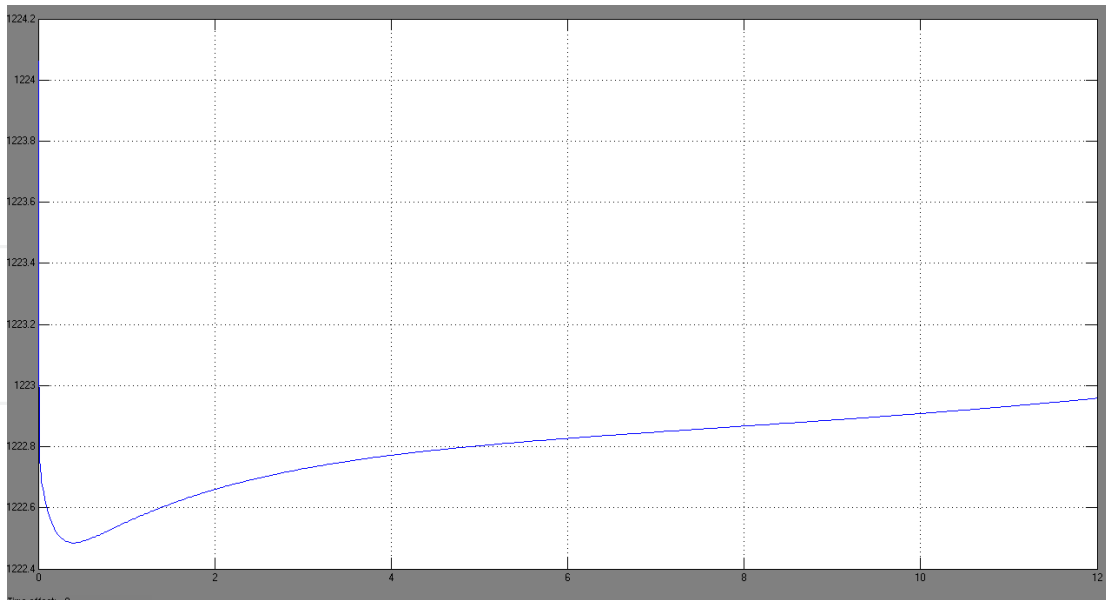
Figure 17. Syngas temperature maintaining at 1223K in the presence of disturbance

9. Conclusion

The development of low order transfer function model are required due to the difficulties encountered in the development of control strategies on ALSTOM benchmark challenge. 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., and reduced order approximation. Some lower order transfer functions obtained using algebraic method are found to have higher error criterion than RGA loop pairing. 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.

The authors have applied PID control algorithms for gasifier control around 100% load. As desired in the challenge problem, step and sinusoidal disturbances have been given in Psink. Preliminary simulation results show that the pressure and temperature of the syngas are controlled within the permissible constraint limits. However the authors intend to do extensive simulations for 100%, 50% and no-load with error due to pressure and temperature setpoints modulating different input variables.

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Appendix A: Transfer function matrix of Alstom plant for 100% load

Transfer function blocks	algebraic method	reduced order approximation
G11	$\dfrac{-43.210273s^2 - 32.8849432314s + 10.5403}{-0.0083690166s^2 + 0.067824414s + 0.0019433}$	$\dfrac{-1.197e004\,s^2 + 330.4\,s + 0.001125}{s^2 + 0.0008608\,s + 2.075e - 007}$
G12	$\dfrac{0.67268851s^2 + 0.22784337s + 1.36739}{8.7409426609s^2 - 6.32996277s - 0.0002336}$	$\dfrac{-3.468\,s^2 - 1.063s - 0.001214}{s^2 + 0.0008608\,s + 2.075e - 007}$
G13	$\dfrac{-29.294957767s^2 + 58.590928399s + 0.99338}{0.9053252009s^2 + 0.217203375s - 0.00002424}$	$\dfrac{108.4\,s^2 + 6.901s - 0.008504}{s^2 + 0.0008608s + 2.075e - 007}$
G14	$\dfrac{11.42165811s^2 - 18.197458774s + 2.892}{-298.17003810s^2 + 56.7756422s - 2.2915}$	$\dfrac{-1.851s^2 + 0.06763\,s - 2.618e - 007}{s^2 + 0.0008608\,s + 2.075e - 007}$
G21	$\dfrac{0.7699194835s^2 - 0.4621252416s + 1.4975}{-0.00005375534s^2 - 0.0000999029s - 3.530 * 10^\wedge - 5}$	$\dfrac{-1.068e005\,s^2 + 43.57s - 0.008799}{s^2 + 0.0008608\,s + 2.075e - 007}$
G22	$\dfrac{0.1119962125834s^2 - 0.335052778707s + 1.5892}{-10.666078439387s^2 - 3.7028097164s - 1.016069 * 10^\wedge - 3}$	$\dfrac{-71.72\,s^2 - 0.1481s - 0.0003245}{s^2 + 0.0008608\,s + 2.075e - 007}$
G23	$\dfrac{-38.1754867787s^2 - 606.4765403s + 1.03212}{-0.176233518s^2 - 0.067401899s + 0.0004235}$	$\dfrac{1.142e004\,s^2 - 14.05s - 0.0005055}{s^2 + 0.0008608\,s + 2.075e - 007}$
G24	$\dfrac{7.589742045s^2 + 3.20126491848s + 0.80506}{66.2192853528s^2 + 13.8974102235s + 0.39192}$	$\dfrac{8.026s^2 + 0.03455s + 4.229e - 006}{s^2 + 0.0008608\,s + 2.075e - 007}$
G31	$\dfrac{7.31943261016s^2 - 83.3609061793s + 0.76028}{-0.011722633s^2 - 0.0005261888s + 2.49106 * 10^\wedge - 5}$	$\dfrac{1.507e005s^2 - 171.7s + 0.01169}{s^2 + 0.0008608\,s + 2.075e - 007}$
G32	$\dfrac{-8.34856920133s^2 + 15.2823278158s + 1.4825}{26.0070991592s^2 + 2.5943768447s + 0.000366}$	$\dfrac{-175.2s^2 + 0.4962s + 0.0008401}{s^2 + 0.0008608\,s + 2.075e - 007}$
G33	$\dfrac{-2.8969959854S^2 - 269.839875362S + 1.645}{-0.1417932867S^2 - 0.05582682S + 0.538723 * 10^\wedge - 4}$	$\dfrac{4288s^2 - 4.413s - 0.006334}{s^2 + 0.0008608\,s + 2.075e - 007}$
G34	$\dfrac{-0.149422569149s^2 + 0.605489884s + 0.8755}{-13.277800585s^2 - 15.075170803s - 0.0538}$	$\dfrac{0.9117s^2 + 0.0606s - 3.372e - 006}{s^2 + 0.0008608\,s + 2.075e - 007}$
G41	$\dfrac{0.989892606658S^2 - 6.37153721233S + 1.5006}{0.0005803934141S^2 + 0.000131142815S - 3.06317 * 10^\wedge - 5}$	$\dfrac{1.941e005s^2 + 48.24s - 0.01016}{s^2 + 0.0008608\,s + 2.075e - 007}$
G42	$\dfrac{0.863152338637S^2 - 1.69330243903S + 2.3304}{-12.329066005S^2 - 3.02684037S - 0.00315996}$	$\dfrac{1.941e005s^2 + 48.24s - 0.01016}{s^2 + 0.0008608\,s + 2.075e - 007}$
G43	$\dfrac{-15.4009119304S^2 - 2940.056236928S + 2.31138}{-0.566750514100S^2 - 0.1874561152S + 0.0021771}$	$\dfrac{1.709e004s^2 + 6.082s + 0.0002203}{s^2 + 0.0008608\,s + 2.075e - 007}$
G44	$\dfrac{201.4423617140688S^2 + 275.7771961791S + 0.81865}{-4192.317426968S^2 - 1162.912156389S - 0.01737}$	$\dfrac{3.079s^2 - 0.02195s - 9.775e - 006}{s^2 + 0.0008608\,s + 2.075e - 007}$

Appendix B: Transfer function obtained of 50% load

Transfer function blocks	algebraic method	reduced order approximation
G11	$\dfrac{82973.885826s + 1.311852}{1978.394989s^2 + 1.308653s + 1.568416e - 05}$	$\dfrac{-1330s^2 + 395.4s + 0.006024}{s^2 + 0.0005765s + 7.203e - 008}$
G12	$\dfrac{-4.151117e - 06s^2 + 0.182109e - 03s + 2.547485}{-2.550036s^2 - 2.54957s - 0.91584e - 04}$	$\dfrac{2.476s^2 - 1.01s - 0.0007864}{s^2 + 0.0005765s + 7.203e - 008}$
G13	$\dfrac{727.803446s^2 - 31191.578014s + 1.266519}{9.782304s^2 - 7.184683s + 0.001618}$	$\dfrac{199.6s^2 + 5.647s + 5.637e - 005}{s^2 + 0.0005765s + 7.203e - 008}$
G14	$\dfrac{633.894001s^2 - 26444.64477s + 1.280635}{11207.461122s^2 - 350.714185s + 0.216796}$	$\dfrac{0.3227s^2 + 0.06097s + 4.256e - 007}{s^2 + 0.0005765s + 7.203e - 008}$
G21	$\dfrac{-7.638891e + 18s + 2.495387}{6.3235e + 14s^2 + 4.938082e + 13s - 7.626576e - 05}$	$\dfrac{-1.839e005s^2 + 56.37s - 0.002357}{s^2 + 0.0005765s + 7.203e - 008}$
G22	$\dfrac{1.016135e - 04s^2 + 0.00445778s + 2.676878}{-29.50425s^2 + 3.382317s - 10.2823689}$	$\dfrac{166s^2 - 0.06141s - 0.0001875}{s^2 + 0.0005765s + 7.203e - 008}$
G23	$\dfrac{-150.691621s^2 - 1.446301e + 12s + 1.682835}{-1.40965e + 08s^2 + 4.809870e + 06s + 0.000157}$	$\dfrac{8739s^2 + 7.32s + 0.0007719}{s^2 + 0.0005765s + 7.203e - 008}$
G24	$\dfrac{0.016439s^2 + 1.190322e + 08s + 1.31212}{2.249456e + 07s^2 + 4.0072857e + 06s + 0.044163}$	$\dfrac{8.171s^2 + 0.02981s + 2.14e - 006}{s^2 + 0.0005765s + 7.203e - 008}$
G31	$\dfrac{470334.30765s + 3.270734}{45.137649s^2 - 1.79416s - 8.741614e - 06}$	$\dfrac{2.322e005s^2 - 243.4s + 0.001665}{s^2 + 0.0005765s + 7.203e - 008}$
G32	$\dfrac{3.716764e - 07s^2 - 160.82437e - 07s + 2.548966}{3.470826s^2 + 3.7707s + 3.13062e - 04}$	$\dfrac{-375.9s^2 + 0.4627s + 0.0005865}{s^2 + 0.0005765s + 7.203e - 008}$
G33	$\dfrac{-3.1067766e + 05s + 2.683919}{-189.668841s^2 - 551.803398s + 0.005885}$	$\dfrac{2926s^2 - 3.597s + 3.286e - 005}{s^2 + 0.0005765s + 7.203e - 008}$
G34	$\dfrac{59112.633568s + 1.437609}{-2.6507907e + 05s^2 - 3511.145849s - 0.053218}$	$\dfrac{-0.4876s^2 - 0.0597s + 3.286e - 005}{s^2 + 0.0005765s + 7.203e - 008}$
G41	$\dfrac{-2.720125e + 07s + 2.501114}{2381.895719s^2 + 740.758982s - 2.580143e - 05}$	$\dfrac{3.296e005s^2 + 24.4s - 0.006982}{s^2 + 0.0005765s + 7.203e - 008}$
G42	$\dfrac{2.01188e - 03s^2 - 0.087054s + 3.7086}{1304.883s^2 + 1.097948e + 05s - 3.3664e - 04}$	$\dfrac{72.72s^2 - 0.4004s - 7.935e - 005}{s^2 + 0.0005765s + 7.203e - 008}$
G43	$\dfrac{5.456232e + 04s + 3.632051}{20.535311s^2 + 20.261304s + 0.000559}$	$\dfrac{1.258e004s^2 + 4.893s + 0.0004882}{s^2 + 0.0005765s + 7.203e - 008}$
G44	$\dfrac{1.2505305e + 04s + 1.333895}{-6380.258041s^2 - 613.370677s - 0.020417}$	$\dfrac{1.715s^2 - 0.02503s - 4.705e - 006}{s^2 + 0.0005765s + 7.203e - 008}$
Gd1	$\dfrac{1.427343e + 06s - 1.570372e + 06}{-8.105303e + 14s^2 - 2.361753e + 11s - 1.1699040e + 07}$	$\dfrac{0.1224s^2 - 2.013e - 005s + 9.669e - 009}{s^2 + 0.0005765s + 7.203e - 008}$
Gd2	$\dfrac{-2.7855e - 06s^2 + 0.122333e - 03s + 1.29029}{41901.74673s^2 + 41909.74673s + 0.3277079e - 03}$	$\dfrac{9.213e - 005s^2 + 3.538e - 007s + 2.198e - 010}{s^2 + 0.0005765s + 7.203e - 008}$
Gd3	$\dfrac{1.319354e + 11s + 2.217903}{2.175717e + 11s^2 - 3.741932e + 11s + 2.32512}$	$\dfrac{0.9534s^2 + 0.0005484s + 6.87e - 008}{s^2 + 0.0005765s + 7.203e - 008}$
Gd4	$\dfrac{2.3313028e + 04s + 1.298735}{2.220288e + 08s^2 - 1.65059e + 09s - 4.327659e + 04}$	$\dfrac{-3.39e - 005s^2 - 3.341e - 008s - 2.163e - 012}{s^2 + 0.0005765s + 7.203e - 008}$

Appendix C: Transfer function obtained of 0% load

Transfer function blocks	algebraic method	reduced order approximation
G11	$$\frac{6412495.306104s + 59.515387}{81552.782731s^2 + 14.789253s + 8.741323e - 05}$$	$$\frac{3.828e004\ s^2 + 561.7\ s\ +\ 0.006739}{s^2 + 0.0002741\ s + 9.897e - 009}$$
G12	$$\frac{5.156462e - 6s^2 + 2.9510432e - 4s + 3.342709638}{-3.34349077s^2 - 3.3438166s - 8.398176626e - 05}$$	$$\frac{79.85\ s^2 -\ 0.955\ s\ -\ 0.0003939}{s^2 + 0.0002741\ s + 9.897e - 009}$$
G13	$$\frac{203764.661731s^2 - 10907532.587163s + 56.60632}{-2370.734866s^2 - 5009.316672s + 0.038167}$$	$$\frac{178.3\ s^2 + 1.338\ s\ +\ 1.467e - 005}{s^2 + 0.0002741\ s + 9.897e - 009}$$
G14	$$\frac{8.872773e + 40s^2 - 4.859238e + 42s + 1.656547}{-1.042016e + 42s^2 - 9.464071e + 40s + 0.032264}$$	$$\frac{3.845\ s^2 + 0.05121s + 5.082e - 007}{s^2 + 0.0002741\ s + 9.897e - 009}$$
G21	$$\frac{-2.966146e + 10s + 114.021444}{1762415.861223s^2 - 382735.79834s + 0.000915}$$	$$\frac{-4.377e005\ s^2 + 120.2\ s\ +\ 0.001232}{s^2 + 0.0002741\ s + 9.897e - 009}$$
G22	$$\frac{-2.21638386e - 03s^2 + 0.1268436s + 3.475304171}{-41.36659216s^2 + 9.7254335s + 3.685291183e - 04}$$	$$\frac{948.2\ s^2 + 0.117\ s -\ 9.333e - 005}{s^2 + 0.0002741\ s + 9.897e - 009}$$
G23	$$\frac{-1.783467s^2 - 4.004262e + 09s + 2.15279}{-392574.725689s^2 - 671071.290709s + 0.000361}$$	$$\frac{4701\ s^2 + 1.852\ s\ +\ 5.905e - 005}{s^2 + 0.0002741\ s + 9.897e - 009}$$
G24	$$\frac{-0.000362s^2 - 573649.046541s + 1.698815}{-81530.566687s^2 - 7775425361s + 0.028148}$$	$$\frac{11.85\ s^2 + 0.02519\ s\ +5.973e - 007}{s^2 + 0.0002741\ s + 9.897e - 009}$$
G31	$$\frac{470334.30765s + 3.270734}{45.137649s^2 - 1.79416s - 8.741614e - 06}$$	$$\frac{5.378e005\ s^2 - 408.2\ s -\ 0.003703}{s^2 + 0.0002741\ s + 9.897e - 009}$$
G32	$$\frac{2.136783444e - 07s^2 - 122.288e - 07s + 3.334867}{4.423179153s^2 + 4.802113698s + 3.116106e - 05}$$	$$\frac{-1552\ s^2 + 0.2945\ s +\ 0.0003176}{s^2 + 0.0002741\ s + 9.897e - 009}$$
G33	$$\frac{67905.569056s + 3.379449}{407.551672s^2 - 1891.8753s - 0.007252}$$	$$\frac{1502\ s^2 - 0.8885\ s\ - 4.612e - 006}{s^2 + 0.0002741\ s + 9.897e - 009}$$
G34	$$\frac{77345.248573s + 1.937428}{-472193.214731s^2 - 1741.323615s - 0.024306}$$	$$\frac{-5.796\ s^2 - 0.05223\ s - 7.889e - 007}{s^2 + 0.0002741\ s + 9.897e - 009}$$
G41	$$\frac{-1.664227e + 08s + 3.266391}{10606.927662s^2 + 1483.255839s - 9.560048e - 06}$$	$$\frac{9.186e005\ s^2 - 25.51\ s - 0.003382}{s^2 + 0.0002741\ s + 9.897e - 009}$$
G42	$$\frac{1.52637013e - 03s^2 - 0.08735416s + 4.8185565}{-2490.9933s^2 - 247081.2502s - 15.27197e - 04}$$	$$\frac{45.08\ s^2 - 0.4357\ s - 3.123e - 005}{s^2 + 0.0002741\ s + 9.897e - 009}$$
G43	$$\frac{187977.323085s + 4.505946}{69.134727s^2 + 119.112126s + 0.001149}$$	$$\frac{6900\ s^2 + 1.238\ s\ + 3.885e - 005}{s^2 + 0.0002741\ s + 9.897e - 009}$$
G44	$$\frac{58954.826124s + 1.729767}{-26761.155753s^2 - 1437.956917s - 0.01438}$$	$$\frac{-4.063\ s^2 - 0.02662\ s - 1.191e - 006}{s^2 + 0.0002741\ s + 9.897e - 009}$$
Gd1	$$\frac{-1.344731e + 23s - 1475658.562121}{2.994947e + 31s^2 + 3.271975e + 26s + 2.050176e + 07}$$	$$\frac{-0.1992\ s^2 - 7.057e - 005\ s - 7.124e - 010}{s^2 + 0.0002741\ s + 9.897e - 009}$$
Gd2	$$\frac{-5.6523279e - 06s^2 + 0.323485e - 03s + 3.3032}{96936.4763s^2 + 179827.0165s + 754.357}$$	$$\frac{-0.0003971\ s^2 + 6.566e - 008\ s\ + 4.334e - 011}{s^2 + 0.0002741\ s + 9.897e - 009}$$
Gd3	$$\frac{-7.490644e + 11s + 2.88116}{-6.847024e + 11s^2 - 2.019168e + 12s + 2.921795}$$	$$\frac{0.9858\ s^2 + 0.0002702\ s\ + 9.76e - 009}{s^2 + 0.0002741\ s + 9.897e - 009}$$
Gd4	$$\frac{-40689.070969s + 1.677564}{-1.634099e + 08s^2 - 9828353.140255s - 264.279412}$$	$$\frac{-1.935e - 005\ s^2 - 6.714e - 009\ s - 6.282e - 014}{s^2 + 0.0002741\ s + 9.897e - 009}$$

Appendix D: Lower order Transfer function reduction

Consider an nth higher order system represented by its transfer function

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

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

$$\text{First Order} = \frac{A_0}{a_1 s + a_0} \tag{5}$$

$$\text{Second order} = \frac{A_1 + A_0}{a_2 s^2 + a_1 s + a_0} \cdots \tag{6}$$

$$\text{n-1 order} = \frac{A_{n-2} s^{n-2} + A_{n-3} s^{n-3} + \cdots + A_2 s^2 + A_1 s + A_0}{a_{n-1} s^{n-1} + a_{n-2} s^{n-2} + \cdots + a_2 s^2 + a_1 s + a_0} \tag{7}$$

Equations (5) through (7) gives the lower order model for higher order system G(s). For n higher order system, (n-1) lower order models can be formulated.

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