EFFICACY OF CLASSICAL TUNING METHOD FOR NONLINEAR MULTI VARIABLE PROCESSES - A CASE STUDY WITH FLUIDIZED BED COAL GASIFIER

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ABSTRACT

Control of coal gasifier during variations in the calorific value of coal is quite complex because of its non linearity and interactions among control parameters. Advanced control strategies are being employed to meet the stringent performance requirements of the gasifier. In this paper, the authors have proposed the classical Chien, Hrones and Reswick (CHR) tuning method for adjusting cPI controller parameters and demonstrated that this method is still giving better results. With these parameters the performance of fluidized bed coal gasifier is examined under pressure disturbance and coal quality variations. It is evident that the results obtained are superior to the existing methods found in literature.

Keywords: alstom benchmark challenge II, fluidized bed coal gasifier, chien, hrones and reswick (CHR) tuning, fuel switching.

1. INTRODUCTION

Electricity touches almost all facets of human life today; it is a key indicator of economic development and standard of living of the people in any country. The current global scenario faced by electric utilities (or power plants) is characterized by many challenges like minimising the cost of power generation, responding instantaneously to grid demands, demands for a high degree of availability and reliability, meeting stringent government regulations on environmental impact, conservation of natural resources etc.,

Currently electricity generation is primarily dependent on coal fired power plants - both conventional and gas turbine based - throughout the world. These plants contribute more than 50 percent of global power generation. This dependence of power generation on coal is likely to be continued in future for next two or three decades also, as the coal is cheap, easily available and distributed throughout the world. The design and performance of thermal power plants and the cost of power generation are influenced by coal properties (also referred to as coal quality). Coal quality impacts not only the coal cost but also the capital, operating and maintenance costs of the plant. Often thermal power plants are not sure of the consistent quality of coal that throughout they will be getting for the power station. In order to take care of this situation, equipment (boiler or coal gasifier) manufacturers are frequently asked to engineer the equipment for using wide range of coals of different quality. Specifying the wide range of coals for the design of the equipment (boiler or coal gasifier) will not allow the manufacturer to select optimum equipment for the particular power station.

Due to coal property variations, the calorific value (heating value) of the coal from the same mine does not remain the same, but varies randomly over an average value. During this situation, fluctuations in the main steam pressure and temperature are noticed even when the load remains constant in a conventional thermal power plant. These fluctuations are due to variations in calorific value of the fuel burnt and the phenomena is often known as " fuel switching" (though the terminology " fuel switching" was earlier used to refer to change of coal source, now it is also used to refer to wide variations in the coal quality within the same mine). Attention has to be given during coal switching since the quality of the coal impacts almost all aspects of plant operation. An effective control strategy to take care of variations in calorific value as and when fuel switching takes place is highly desirable from the operational point of view. Against this background, it motivated the researcher to aim for an improved control to effectively handle load disturbances and fuel switching in a coal gasifier in an Integrated Gasification Combined Cycle (IGCC) power plant.

Integrated Gasification Combined Cycle plants: A coal gasifier is a main subsystem in a IGCC plant. A coal gasifier converts coal into syngas with certain calorific value. Coal, steam and air react within the gasifier and syngas (also known as fuel gas) is produced. Figure-1 shows the schematic of coal gasifier. The syngas is used as fuel in a gas turbine provided in the downstream of gasifier and electrical power is generated. The flow rate of syngas to the gas turbine is controlled through a valve provided at the inlet of turbine. Due to disturbances emanating from gasifier input side (changes in the calorific value of the coal fed into gasifier) and output side (Load changes in gas turbine and frequency fluctuations in the grid), the pressure and temperature of syngas produced fluctuates. However, the pressure and temperature of syngas is to be maintained at specified values at the inlet of the gas turbine irrespective of operating points. Therefore the control problem is to study the transient behaviour 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

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control the pressure and temperature of the syngas at the inlet of gas turbine for any variation in gas turbine load - which in turn affect throttle valve movement - without undue overshoots and undershoots. This calls for an efficient control strategy satisfying the specified performance criteria during disturbances.

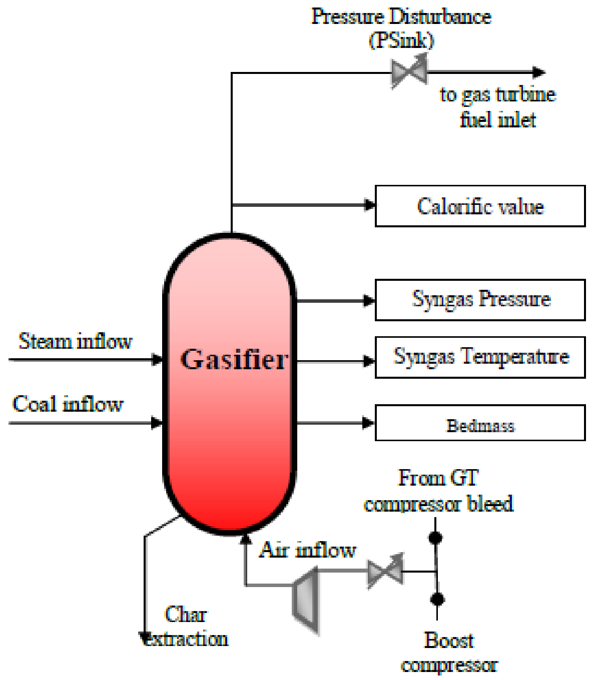

Figure-1. Schematic of a coal gasifier.

In recent times the research community have opted the modern control techniques such as Fuzzy logic controllers, Artificial Neural Network, Neuro-Fuzzy controller, Model Predictive Controllers, State Feedback Controllers, State observer techniques with feedbacks to control complex process variables [39-46]. These techniques are quite complex since it requires comprehensive knowledge and mathematical description of the plant. The developments take place so fast in this direction raise a doubt whether PID controller will survive in the future [1]. On the other hand, classical PID controllers are proved to be the best controllers due to its simplicity and stability. The performance of the PID controllers is adjudicated by the selection of its parameters. There are several tuning methodologies available in literature. Selection of suitable tuning algorithm depends on the knowledge about the system to be controlled. One of such algorithm called Chien, Hrones and Reswick (CHR) is widely used for tuning the single loop PID controller by researchers in the past [2-6]. In this paper, the authors have applied the classical CHR method for tuning classical PI controllers of the fluidized bed coal gasifier.

2. ALSTOM BENCHMARK CHALLENGE FOR COAL GASIFIER

A Coal gasifier is a highly nonlinear higher order (25^{th} order) system with four inputs and four outputs with higher degree of cross coupling between the input and output variables. The statespace model of ALSTOM gasifier [7] [8] is given by:

$$\dot{X} = Ax(t) + Bu(t)$$
$$Y = Cx(t) + Du(t) \tag{1}$$

Where,

x(t)	= internal state matrix of gasifier (25 x 1)
u(t)	= input variable matrix (6 x 1)
A	= system matrix (25 x 25)
B	= input matrix (25 x 6)
Y	= output variables matrix (4 x 1)
C	= observable matrix (25 x 4)
D	= disturbance matrix (4 x 6)

The system matrix is of 25^{th} order and analysis and control of such higher order system relatively difficult. In this connection, ALSTOM - a multinational and Original Equipment Manufacturer (OEM) developed a detailed nonlinear mathematical model and validated against the operational data obtained from a prototype of gasifier of 87 MW capacities [7] [8]. Further, ALSTOM has made the model available to the academic community and demanded different control strategies which will satisfy certain stringent performance criteria during specified disturbances. These demands of ALSTOM are well known as “ALSTOM Benchmark Challenges”. This paper deals with providing solution to Alstom Benchmark Challenges using CHR tuning of PID controller. The details of the steady state values and the limits for the input and output variables are given in Table-1 and Table-2 respectively.

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Table-1. Input variables and limits.

Input variables	Steady state values			Limits		
	100% load	**50% load**	**0% load**	**Maximum inflow**	**Minimum Inflow**	**Rate ($kg\ s^{-2}$)**
Char extraction WCHR ($kg\ s^{-1}$)	0.9081	1.1887	1.554	3.5	0	0.2
Air inflow WAIR ($kg\ s^{-1}$)	17.422	12.125	6.559	20	0	1.0
Coal inflow WCOL ($kg\ s^{-1}$)	8.545	6.844	5.158	10	0	0.2
Steam inflow WSTM ($kg\ s^{-1}$)	2.705	2.007	1.236	6.0	0	1.0

Table-2. Output variables and limits.

Output variables	Setpoint			Allowed fluctuations
	100% load	**50% load**	**0% load**	
Calorific value CVGAS ($MJ\ kg^{-1}$)	4.3584	4.472	4.6871	± 0.01
Bedmass MASS (kg)	10000	10000	10000	± 500
Syngas Pressure PGAS (bar)	19.9996	15.7112	11.469	± 0.1
Syngas Temperature TGAS (°K)	1221.6	1159.59	1066.4	± 1

These constraints on input and output variables should be satisfied at 0%, 50% and 100% operating conditions under pressure disturbance and coal quality variations. Asmer *et al*. [9] investigated four different control strategies based on Relative Gain Array (RGA) loop paring approach and concluded that scheme 4 (later this scheme was included in ALSTOM benchmark challenge II and termed as Baseline PI controller) in which four SISO controllers had been employed as shown in Table-3. This Baseline controller was implemented on Benchmark challenge which dealt with only pressure disturbance test [7]. All the performance requirements were satisfied at 50% and 100% load conditions while, performance violation in Pressure of the syngas was reported at 0% load with sinusoidal pressure disturbance.

Table-3. Controllers employed for various process parameters.

S. No	Inputs	Outputs	Controller
1	Air flow rate	Calorific value	PI
2	Char flow rate, Coal flow rate	Bedmass	P, P
3	Steam flow rate	Pressure	PI
4	Char flow rate	Temperature	PI

This particular aspect has been posed as a control challenge problem for gasifier by ALSTOM. Researchers have adopted numerous classical / advanced control techniques [10-24] so as to meet the constraints. The disturbance rejection performance of different control structures of ALSTOM gasifier was evaluated using Generalised Relative Disturbance Gain (GRDG) by Agustriyanto *et al*. [28]. AlSeyab *et al*. [28-29] applied nonlinear model predictive control to identify the pressure of the gas. Chin *et al* [31] performed the analysis and robust controller design for the gasifier system using H2 methodology. Loop shaping H-infinity controller design was employed by Preampain et.al [32] for the design of regulator. Decoupler was developed for the gasifier by Ranjith et.al [33]. Rice *et al*. [36] proposed predictive control that uses linear quadratic optimal inner loop and the outer loop is supervised by predictive controller. Tan *et al*. [34] proposed partially decentralized controller design method with constraints on the inputs and outputs of the gasifier. Proportional Integral plus (PIP) by Taylor *et al*. [35-37] was designed based on discrete time model of the plant. An approach based on the state estimation was applied to the gasifier control by Wilson et.al [38].

However satisfying the performance requirements at all load conditions in the presence of disturbances at input and output side of the gasifier still remains

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challenging. The main difficulty lies in obtaining appropriate controller parameter values. These values are normally obtained by trial and error procedure or through iterative algorithms. The authors have adopted CHR method of tuning the decentralized controller.

3. DETERMINATION OF PID CONTROLLER CONSTANTS

Chien, Hrones and Reswick (CHR) modified the step response method of (Ziegler Nichols Method) PID tuning which provided better damped closed-loop systems. They used 'quickest response without overshoot' or 'quickest response with 20% overshoot' as design criteria in the proposed method [25-27]. They also found that tuning for set point change and load disturbance are different. The tuning parameters of 'a' and 'L' are determined and tuning is done using these two parameters. This method has been employed for different processes by the researchers such as control of multivariable system [2], for controlling the main steam pressure of 500 MW steam generators [3] [4], air pressure control [5] and for controlling an unstable electronic circuits [6].

In this work, load disturbance response method with 0% overshoot of CHR is applied to determine the controller parameters. Further in this paper, it has been demonstrated that transient responses during input side and load disturbances obtained through classical CHR method are much better than earlier published results. The values of 'a 'and 'L' are employed to calculate the PID controller tuning parameters. Consider a 2nd order system of the general form.

$$G(s) = \frac{\omega_n^2}{s^2+2\xi\omega_n s+\omega_n^2} \quad (2)$$

Time constant (τ) is given by ξ/ω_n. The value of 'L' is given by 0.1τ. The value of 'a' is determined by the gain of the system. This method is employed to calculate the parameters 'a' and 'L' of the system. Table IV depicts the calculated PI controller parameters using CHR tuning method.

Table-4. CHR tuning method.

Controller Mode	CHR Method with 0% Overshoot			CHR method with 20% Overshoot		
	K_p	T_i	T_d	K_p	T_i	T_d
P	0.3/a			0.7/a		
PI	0.6/a	4L		0.7/a	2.3L	
PID	0.95/a	2.4L	0.42L	1.2/a	2L	0.42L

In this work, load disturbance response method with 0% overshoot of CHR is applied to determine the controller parameters. Further in this paper, it has been demonstrated that transient responses during input side and load disturbances obtained through classical CHR method are much better than earlier published results. The values of 'a 'and 'L' are employed to calculate the PID controller tuning parameters. As CHR method requires 2nd order transfer function model of the plant, the 25th order coal gasifier statespace model is reduced to 2nd order transfer function model using Balance realization technique and the expected model will be in the form;

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} & G_{13} & G_{14} \\ G_{21} & G_{22} & G_{23} & G_{24} \\ G_{31} & G_{32} & G_{33} & G_{34} \\ G_{41} & G_{42} & G_{43} & G_{44} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} + \begin{bmatrix} G_{d1} \\ G_{d2} \\ G_{d3} \\ G_{d4} \end{bmatrix} d \quad (3)$$

Where,

y_1 = Fuel gas calorific value (J/kg)
y_2 = Bedmass (tonns)
y_3 = Fuel gas pressure (bar)
y_4 = Fuel gas temperature (K)
u_1 = char extraction flow (kg/s)
u_2 = air mass flow (kg/s)
u_3 = coal flow (kg/s)
u_4 = steam flow (kg/s)
d = sink pressure (bar)

The obtained 2nd order model is used for calculating PI controller parameters using CHR method and the results are shown in Table-5.

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Table-5. Tuning parameters for decentralized PI controller using CHR method.

Pairing	Transfer function	a	L	Kp	Ki
G_{12}	$\frac{-1.851s^2-0.06763s-0.0000002618}{s^2+0.0008608s+2.023715e^{-007}}$	1.29366	-	0.2319	
G_{14}	$\frac{4388s^2+4.413s+1.78}{s^2+1198.98s+5.01}$	0.3561253	23.9318	1.6848	0.0176
G_{21}	$\frac{-80.1s^2+0.955s-0.00001453699}{s^2+0.00001391757s+9.89e^{-009}}$	1469.8677	1407.2369	4.0820e-4	7.2515e-8
G_{43}	$\frac{0.9117s^2+0.0606s+3.9320}{s^2+0.45873263s+2.299957e^{-003}}$	1709.5965	19.945	3.5096e-4	4.398e-6

4. PERFORMANCE TESTS

The efficacy of decentralized PI controller which is optimally tuned by CHR method is examined under pressure disturbance test, load change test and coal switching test. The response should satisfy the performance requirements stated in table I and table II at all operating conditions (0%, 50% and 100%).

4.1 Pressure disturbance test

The following two pressure disturbance tests (PSink) are to be performed.

a) A step disturbance of - 0.2 bar, corresponding to a sudden opening of fuel (syngas) inlet valve to the gas turbine.

b) A sinusoidal disturbance of amplitude -0.2 bar, and frequency of 0.04Hz, corresponding to low frequency movements of fuel inlet valve to the gas turbine representing changes in grid frequency.

The plant is initialized at 100% load and a step disturbance of - 0.2 bar is applied at t = 30 second (given in ALSTOM benchmark Challenge). The response is recorded for 300 seconds and performance violation on input and output variables, if any is noted. This procedure is repeated for 50% and 0% loads. Figure-2 shows the response of the gasifier at 0%, 50% and 100% load conditions for step and sinusoidal disturbances respectively.

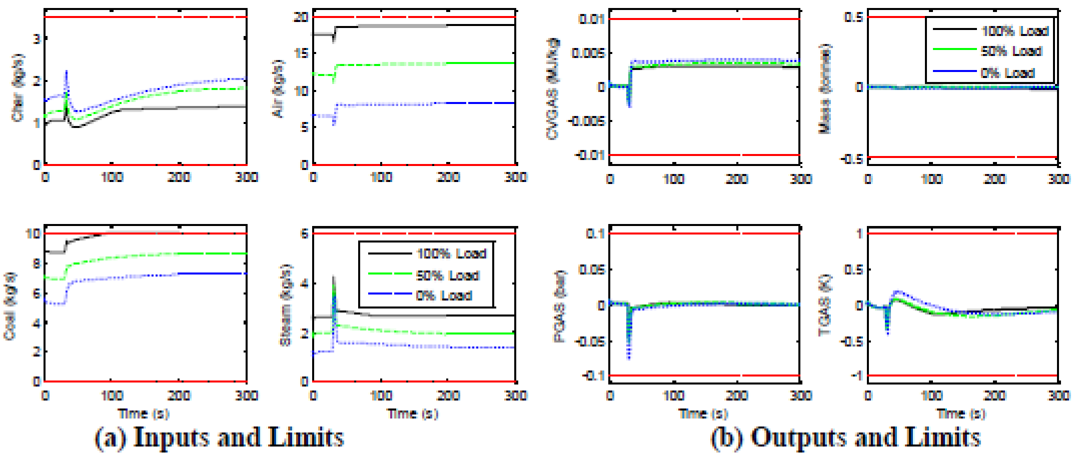

Figure-2. Response to step change in PSink disturbance at 0%, 50% and 100% load conditions.

The performance is also verified for sinusoidal disturbance and it is shown in Figure-3. It is noted that the input and output variables strictly follows the constraints (denoted in red color dashed line). All the variables are within the acceptable limits while violation in PGAS at 0% load condition for sinusoidal pressure disturbance is reported by researchers in the past.

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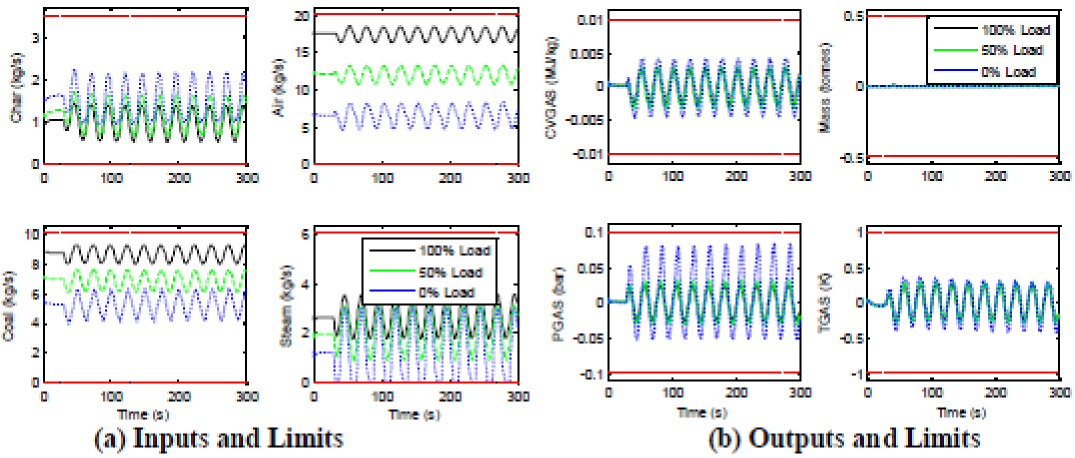

Figure-3. Response to sinusoidal change in PSink disturbance at 0%, 50% and 100% load conditions.

The CHR method of tuning the PI controller has been applied to study the transient analysis of gasifier output variables like the calorific value of gas, bedmass, pressure and temperature of gas during load disturbances. The Maximum Absolute Error (MAE) and the Integral Absolute Error (IAE) have been calculated and compared with Baseline PI control [8], Genetic Algorithm based PI controller (Simm and Liu 2006 [18]), Bat Algorithm based PI (Kotteeswaran and Sivakumar 2013[14], Cuckoo Search algorithm based PI (Kotteeswaran and Sivakumar 2014 [19]), Firefly Algorithm based PI (Kotteeswaran and Sivakumar 2014 [16]), Particle Swarm Optimization based PI (Kotteeswaran and Sivakumar 2014 [15]).

Performance indices such as MAE and IAE are calculated and are shown in Table-6 and Table-7 respectively for the output variables - Calorific value of syngas, bedmass, Pressure and Temperature. It is seen that IAE values are larger for step change pressure disturbance and getting reduced for sinusoidal disturbance. The results show remarkable improvement in the response which motivates the author to further proceed with the load change test and coal switching test.

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Table-6. Maximum Absolute Error at 0%, 50% and 100% loads for step and sinusoidal pressure disturbances.

Outputs	Baseline PI	Simm A	BA-PI	CS-PI	FA-PI	PSO-PI	CHR-PI
Step, 100% load							
CVGAS(KJ/kg)	4.853	4.236	5.722	6.074	5.364	6.087	3.14741
MASS(kg)	6.94	6.95	6.94	6.94	6.94	6.95	8.285
PGAS(Pa)	0.0499	0.0513	0.0425	0.0410	0.0448	0.0411	0.04485
TGAS(K)	0.2395	0.2244	0.2660	0.2786	0.2535	0.2792	0.33324
Step, 50% load							
CVGAS(KJ/kg)	5.031	4.460	6.295	6.723	5.878	6.739	3.5358
MASS(kg)	8.45	8.45	8.45	8.45	8.45	8.45	10.053
PGAS(Pa)	0.0577	0.0592	0.0510	0.0496	0.0526	0.0495	0.05
TGAS(K)	0.2660	0.2477	0.3024	0.3187	0.2863	0.3193	0.35577
Step, 0% load							
CVGAS(KJ/kg)	5.891	4.706	7.249	8.018	6.696	8.053	3.9769
MASS(kg)	11.05	11.06	11.05	11.05	11.05	11.06	13.07
PGAS(Pa)	0.0772	0.0785	0.0760	0.0760	0.0760	0.0760	0.079
TGAS(K)	0.3232	0.3018	0.3818	0.4034	0.3584	0.4042	0.41127
Sine, 100% load							
CVGAS(KJ/kg)	4.102	2.401	3.731	3.756	3.702	3.758	2.77694
MASS(kg)	10.86	10.17	10.72	10.76	10.68	10.76	10.803
PGAS(Pa)	0.0496	0.0405	0.0318	0.0291	0.0348	0.0290	0.025547
TGAS(K)	0.3784	0.2806	0.3485	0.3523	0.3442	0.3524	0.28284
Sine, 50% load							
CVGAS(KJ/kg)	4.712	2.712	4.257	4.304	4.211	4.307	3.19962
MASS(kg)	12.85	11.99	12.66	12.72	12.61	12.72	12.861
PGAS(Pa)	0.0623	0.0495	0.0396	0.0363	0.0430	0.0362	0.031
TGAS(K)	0.4226	0.3107	0.3862	0.3912	0.3805	0.3915	0.3166
Sine, 0% load							
CVGAS(KJ/kg)	5.858	3.486	6.100	6.860	5.805	6.908	4.6964
MASS(kg)	16.35	15.53	16.24	16.30	16.18	16.30	16.5535
PGAS(Pa)	0.1196	0.0904	0.0998	0.0991	0.0999	0.0992	0.0828
TGAS(K)	0.4791	0.3757	0.4747	0.5144	0.4504	0.5164	0.42912

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Table-7. Integral of Absolute Error at 0%, 50% and 100% loads for step and sinusoidal pressure disturbances.

Outputs	Baseline PI	Simm A	BA-PI	CS-PI	FA-PI	PSO-PI	CHR-PI
Step, 100% load							
CVGAS(KJ/kg)	30.49	21.46	33.51	34.96	32.18	35.03	803.999
MASS(kg)	795	770	769	766	770	769	1099.34
PGAS(Pa)	0.388	0.668	0.786	0.711	0.864	0.716	0.45811
TGAS(K)	32.45	25.33	31.54	31.67	31.41	31.66	21.7673
Step, 50% load							
CVGAS(KJ/kg)	32.22	23.59	35.77	37.15	34.12	37.22	912.718
MASS(kg)	422	906	443	442	445	440	1927.91
PGAS(Pa)	0.467	0.831	1.039	0.960	1.127	0.948	0.7282
TGAS(K)	38.43	31.30	36.93	37.07	36.76	37.10	31.513
Step, 0% load							
CVGAS(KJ/kg)	43.86	30.75	45.26	46.58	43.95	46.70	1039.95
MASS(kg)	668	834	569	574	564	575	2024.41
PGAS(Pa)	0.595	0.868	2.338	2.237	2.478	2.142	0.762
TGAS(K)	38.39	29.56	35.42	35.71	35.12	35.75	30.383
Sine, 100% load							
CVGAS(KJ/kg)	773.94	450.36	698.18	703.34	692.15	703.64	509.416
MASS(kg)	2076	2073	2076	2075	2077	2075	2402.08
PGAS(Pa)	9.282	7.412	5.942	5.429	6.485	5.414	4.78499
TGAS(K)	67.00	49.09	61.57	62.21	60.84	62.24	47.8675
Sine, 50% load							
CVGAS(KJ/kg)	879.66	506.18	794.24	802.54	785.57	803.01	581.153
MASS(kg)	2522	2516	2519	2517	2521	2517	2906.55
PGAS(Pa)	11.506	9.125	7.343	6.725	7.993	6.706	5.934
TGAS(K)	74.72	54.11	68.10	69.13	66.99	69.18	54.00
Sine, 0% load							
CVGAS(KJ/kg)	1039.51	640.64	1015.34	1061.80	988.99	1063.59	780.684
MASS(kg)	3007	3157	3060	3041	3089	3040	3475.57
PGAS(Pa)	19.145	14.427	13.627	13.122	14.135	13.114	11.566
TGAS(K)	79.54	64.37	79.25	82.10	77.64	82.21	68.75

4.2 Load change test

This test facilitates the evaluation of controller performance across the full operating range of the plant. The plant model is initialized to represent 0% load (House load) and then increased continuously to 50% load at the rate of 5% per minute. Similarly ramp load test from 50% to 100% is done. The proposed controller should ensure the following:

- Stability of the gasifier across the operating region.
- Fluctuations of the input variables should lie within the limits.
- The peak overshoots and undershoots at the end of the ramp input should meet the constraints.

Figure-4 (a) represents the load change from 50% to 100% and the response of the output variables. Figure-4 (b) shows the input variables to load change from 50% to 100%. It is observed that all the outputs track the setpoint without violating the performance constraints. There are very small overshoots and undershoots observed in the response.

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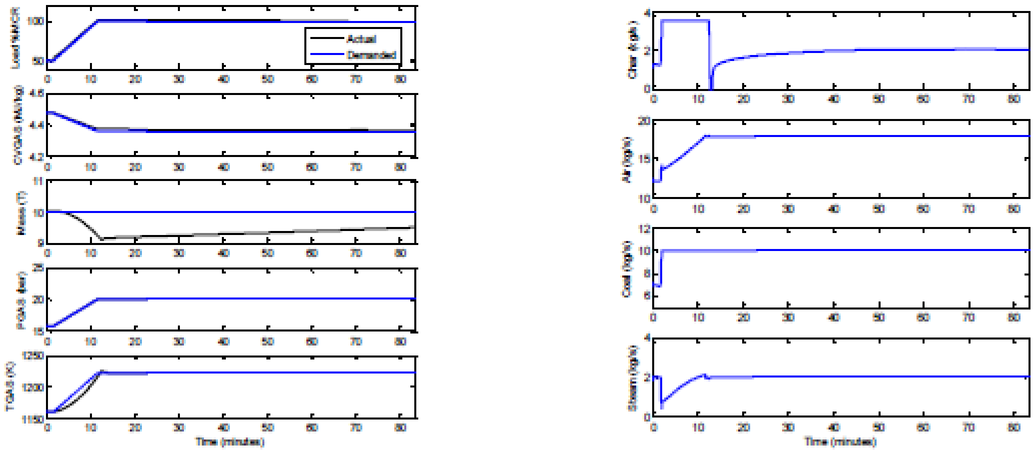
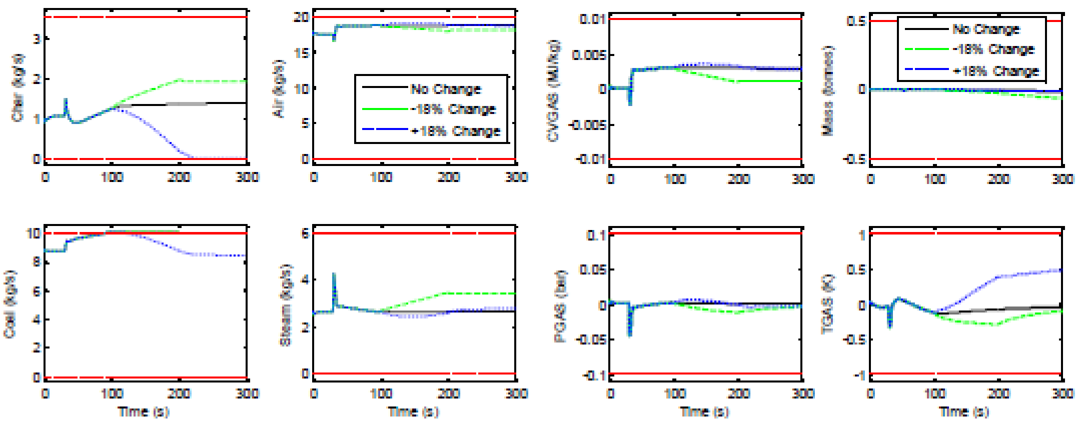


a) Load and Output variables b) Input variables

Figure-4. Response of Output variables and Input variables for load increase from 50% to 100% load.

4.3 Coal switching test

The investigation on the performance of the proposed controller during the disturbances in PSink (output side of gasifier) and change in calorific value of the coal (input side of gasifier) are to be simultaneously introduced to the plant model. Accordingly, six types of pressure disturbance tests are conducted along with change in calorific value of the fuel and are shown in Figures 5 to 10. The maximum allowable limits for coal quality variations are ± 18% with respect to the original calorific value of the coal, beyond which the reactions inside the gasifier will not provide coal gas with designed calorific value.



(a) Inputs and Limits (b) Outputs and Limits

Figure-5. Responses at 100% load for step change in PSink coupled with change in coal quality.

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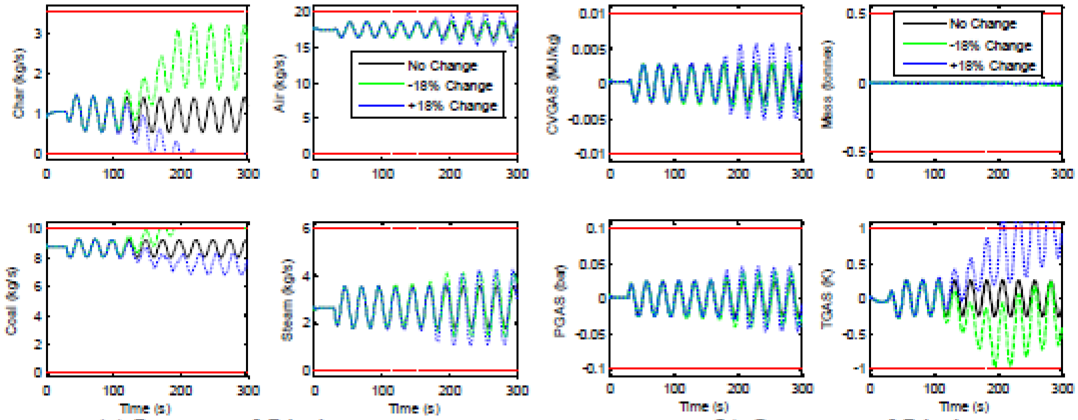
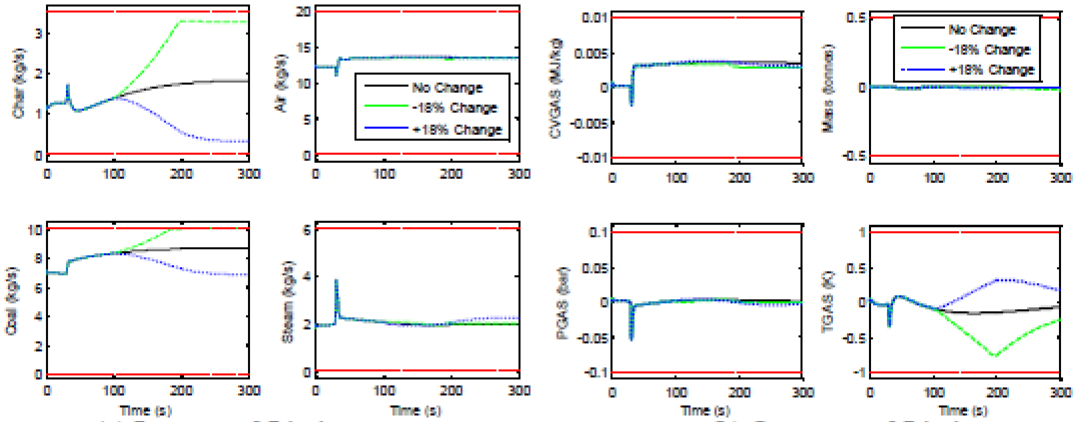


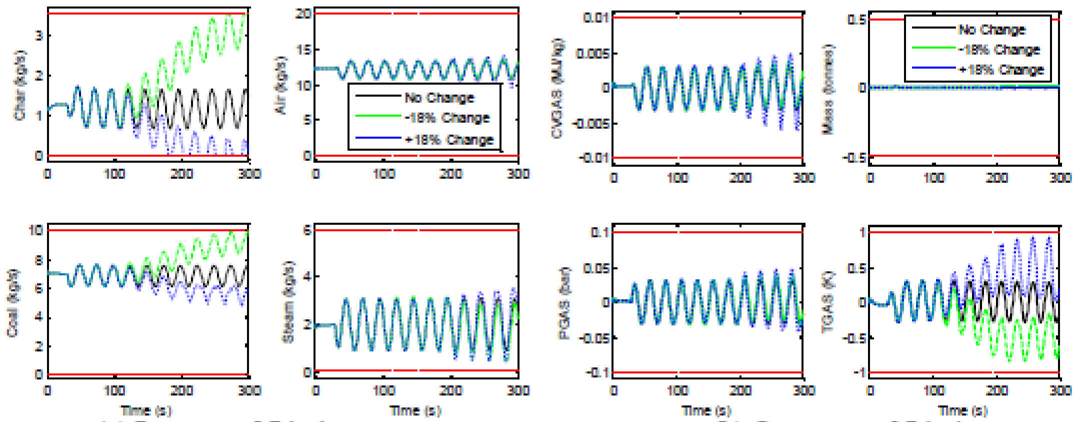
(a) Inputs and Limits (b) Outputs and Limits

Figure-6. Responses at 100% load for step change in PSink coupled with change in coal quality.



(a) Inputs and Limits (b) Outputs and Limits

Figure-7. Responses at 50% load for step change in PSink coupled with change in coal quality.



(a) Inputs and Limits (b) Outputs and Limits

Figure-8. Responses at 50% load for sinusoidal change in PSink coupled with change in coal quality.

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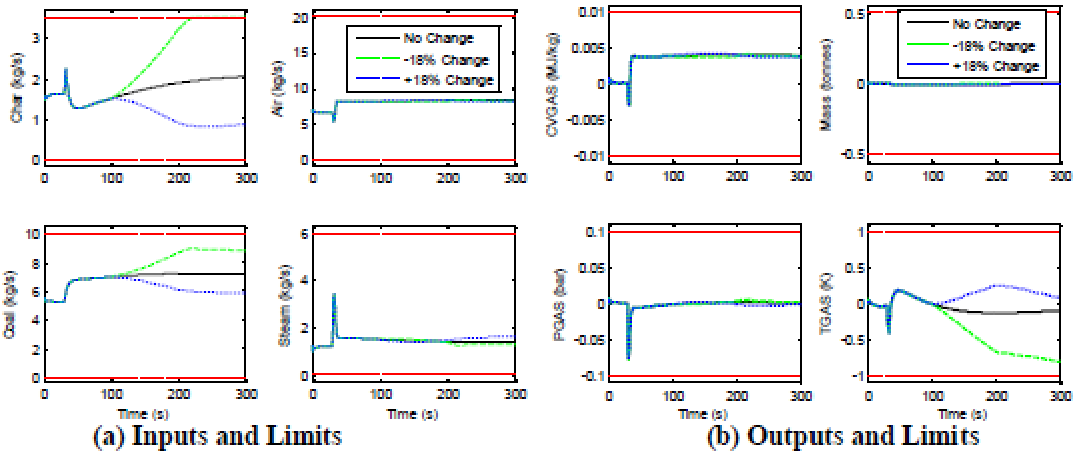

Figure-9. Responses at 0% load for step change in PSink coupled with change in coal quality.

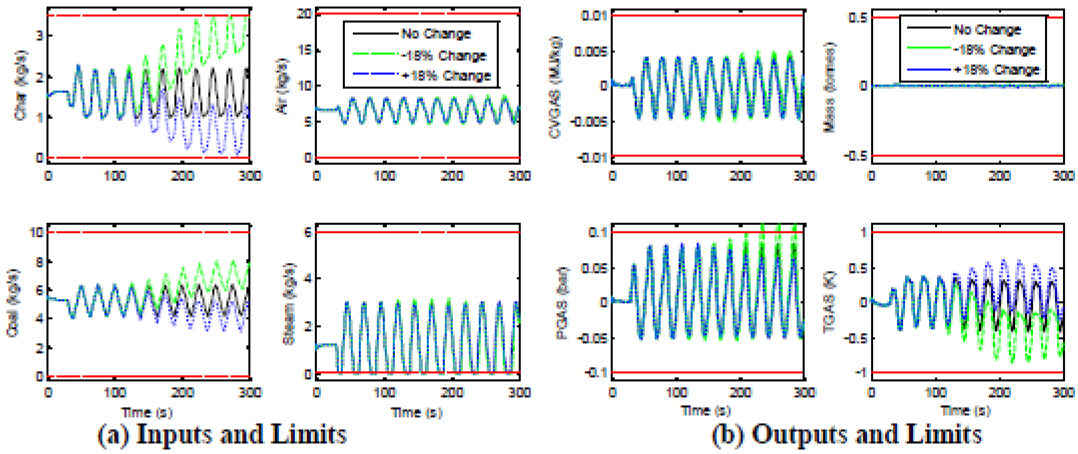

Figure-10. Responses at 0% load for sinusoidal change in PSink coupled with change in coal quality.

As on date, no control strategy ensured this requirement. According to published results, various control strategies met different % of variations in calorific value of coal both in positive and negative directions. An index of coal quality flexibility is defined as:

$$J_{CQ}= \sum_{m=1}^{6} CQ_{upper}^{m} - CQ_{lower}^{m} CQ_{upper}^{m} \quad (4)$$

where CQ_{lower}^{m} represent upper and lower limits of coal quality change percentage. From the obtained results, coal quality flexibility is calculated.

The allowable coal quality variation below which the outputs meet the performance requirements is studied and shown in Table-8 where the extent of the allowed coal quality variations by different control strategies employed like Baseline PI, PI with Genetic Algorithm, PI with Bat Algorithm, PI with Cuckoo Algorithm, PI with Fire Fly Algorithm, PI with Particle Swarm Optimization, PADRC, MOPI, SOPI, Active Disturbance Rejection Control, Multi Objective Active Disturbance Rejection Control and proposed PI controller with CHR algorithm are demonstrated. The terms in the brackets represent the minimum and maximum limit of coal quality flexibility that has been achieved by the corresponding controllers. Input variables such as char extraction, coal inflow and steam inflow deviates the constraints. These are associated with the control valve dynamics and hence they are not considered as major violation.

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Table-8. Comparison of allowed coal quality variation (%).

Load	**100%**		**50%**		**0%**		**Coal quality flexibility**
Disturbance	**Sine**	**Step**	**Sine**	**Step**	**Sine**	**Step**	
Baseline PI	(-14,11)	(-18,18)	(-18,16)	(-18,18)	(0,0)	(-18,18)	167
Simm A	(-13,8)	(-5,14)	(-14,14)	(-12,18)	(0,5)	(-8,18)	129
BA-PI	(-15,12)	(-18,18)	(-18,17)	(-18,18)	(0,4)	(-18,18)	174
CS-PI	(-15,12)	(-18,18)	(-18,17)	(-18,18)	(0,6)	(-18,18)	176
FA-PI	(-16,12)	(-18,18)	(-18,18)	(-18,18)	(0,3)	(-18,18)	175
PSO-PI	(-15,12)	(-18,18)	(-18,18)	(-18,18)	(0,6)	(-18,18)	177
PADRC	(-18,6)	(-17,14)	(-18,10)	(-12,18)	(-18,18)	(-8,18)	175
MOPI	(-13,8)	(-5,14)	(-14,14)	(-12,18)	(-3,18)	(-8,18)	145
SOPI	(-13,8)	(-6,13)	(-14,14)	(-12,18)	(-4,18)	(-8,18)	146
ADRC	(-16,5)	(-14,11)	(-18,7)	(0,4)	(-17,16)	(-18,18)	144
MOADRC	(-17,6)	(-14,11)	(-18,8)	(-17,17)	(-1,18)	(-18,18)	163
CHR-PI	(-18,12)	(-18,18)	(-18,18)	(-18,18)	(-8,18)	(-18,18)	200

5. RESULTS AND ANALYSIS

The CHR method of tuning the PI controller has been applied to study the transient analysis of gasifier output variables like the calorific value of syngas, bedmass, pressure and temperature of syngas during load disturbances (D1 to D6). The Integral Absolute Error (IAE) and the Maximum Absolute Error (MAE) have been calculated and compared with the results from other controllers. In CHR method, it is noted that the input and output variables strictly follows the given constraints. The results show remarkable improvement in the response which motivates the researcher to carry out and verify the performance by the load change test and coal quality change (coal switching) test. In the load change test, the load was changed from 50% to 100% in a ramp fashion. The capability of the controller to keep all the input and output variables within the specified tolerance limits during the closed loop performance was examined in this test. It is worthwhile to mention that the proposed CHR method as well as other control strategies proposed by various investigators met this requirement.

One of the prime objective in Alstom Challenge II problem is to investigate the performance of gasifier during pressure disturbance tests coupled with coal quality (coal switching) change. The philosophy behind these tests is to ascertain to what extent the variation in calorific value of the coal could be met with using certain control strategy. Alstom Challenge II problem envisages a variation of +18% and -18% step change in calorific value of the coal fed into the gasifier. It can be noted that the proposed PI controller with CHR algorithm accommodates the maximum range in coal quality variations from +18% to -18% during all disturbances. Simulation results on closed loop performance of gasifier during a set of specified disturbances are consolidated and the findings are compared (Table VI, VII, VIII, IX) with those obtained by various investigators employing different control strategies.

- Pressure disturbance test shows that the controller is able to track the setpoint in the presence of step / sinusoidal disturbances.
- Very small peak overshoots and undershoots are produced during load change test which is also with in the limits of constraints.
- Coal switching test provides most challenging results which surpasses the results found in literature.

Table-9. Violation variables under coal quality change (± 18%).

Load	**100%**		**50%**		**0%**	
Disturbance	Sine	Step	Sine	Step	Sine	Step
Coal quality Increase (+18%)	Char↓ Tgas↑	Coal↑ Char↓	Char↓	-	Char↓ WStm↓	-
Coal quality decrease (-18%)	Coal↑	Coal↑	-	Coal↑	Pgas↑ Char↑ WStm↓	Char↑

After having compared the performance of gasifier (Closed loop gasifier performance) for different disturbance scenario by various control strategies, it is opined that the proposed PID controller using CHR tuning seems to be the best in the sense that the controller has holistically met most of the performance requirements of Alstom challenge II in comparison with other controllers.

6. CONCLUSIONS

Tuning of PID controllers for complex processes has been a big challenge. In this paper, classical PID controller using CHR tuning method is used for studying the performance of ALSTOM challenge problems. The PID constants are evaluated using CHR tuning method. Performance tests are conducted at all load conditions. This technique permits greater flexibility of operation during fuel switching with moderate deviations in controlled variables. The same PID controllers using CHR tuning method can be employed for any other complex systems like distillation column, desalination system etc., which are considered as highly nonlinear systems with multiple inputs and outputs with higher degree of cross coupling between the input and output variables.

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Notations	
ISE	Integral Squared Error
ISA	Integral Squared Absolute Error
MAE	Maximum Absolute Error
SimmA	SimmA is the abbreviation used to represent the result obtained by a researcher - Simm, A and Liu, GP., 2006.
BA-PI	Bat Algorithm based PI Controller
CS-PI	Cuckoo Search algorithm based PI Controller
FA-PI	Firefly Algorithm based PI controller
PSO-PI	Particle Swarm Optimization based PI controller
PADRC	Partial Active Disturbance Rejection Control
MOADRC	Multi Objective Active Disturbance Rejection Control
MOPI	Multi Objective based Proportional Integral
SOPI	Single Objective based Proportional Integral
Subscripts	
a	intercept values in Y-axis (designated as ‘a’) from the open loop step response of the output
L	intercept values in X-axis (designated as “L”) from the open loop step response of the output
t	time

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