CHAPTER 4

CLOSED LOOP PERFORMANCE OF THE GASIFIER – LOMs COUPLED WITH PID FILTER CONTROLLER

4.1 INTRODUCTION

Based on a survey of over eleven thousand controllers in the process industries, 97% of regulatory controllers utilize classical PID algorithms to process the error signal and derive the control signal for the actuating elements/mechanisms (Desborough Honeywell, 2001). PID controller lends itself for easiest way of implementation either in hardware or software. The PID controller exists in different forms such as a stand-alone controller, part of a Direct Digital Control package or distributed process control system or a control segment implicitly built into embedded systems. Thousands of instrument and control engineers worldwide are using such controllers in their daily work.

4.2 PROPORTIONAL-INTEGRAL-DERIVATIVE-FILTER CONTROLLER

A typical system/process with a PID controller is shown in figure 4.1

![Figure 4.1 Closed loop representation of process with PID controller](image)
The control signal $u(t)$ is the output of the PID controller and is given by:

$$u(t) = ke(t) + ki \int_0^t e(t) \, dt + kd \frac{de}{dt}$$

(4.1)

where $e(t)$ is the error signal obtained as the difference between the desired value, $r(t)$ and actually measured value $y(t)$. The reference value is also commonly called the set point. The control signal is thus a sum of three terms:

- $u_p(t) =$ error multiplied by $K_p$
- $u_i(t) =$ Integral of the error multiplied by $K_i$
- $u_d(t) =$ Derivative of the error multiplied by $K_d$.

However, one of the most common problems associated with PID is with the synthesis of derivative action. Ideal derivative has very high gain, and is susceptible for noise accentuation (Desborough Honeywell, 2001). Hence the PIDF (Proportional–Integral-Derivative-Filter) controller are chosen, whose derivative action is represented as below:

$$Da = \frac{K_d s}{1 + sT_f}$$

Here $T_f$ is called filtering time and is chosen as $T_f = \frac{K_d}{N}K_p$ where $N$ is the filter coefficient and it can range between 2 to 100. The implementation of PIDF controller is schematically shown in Fig 4.2.

![Fig 4.2 Parallel realization of PIDF controller](image-url)
The transient response of a system depends upon the choice of $K_p$, $K_i$ and $K_d$ values. Usually the control engineers will fix these parameters based on their experience or determined using tuning map concept. Basically a tuning map concept involves trial and error method and labourers. Further, trial and error method will not necessarily lead to a successful determination of the required control parameters.

Hence this problem of obtaining suitable controller parameter has been conceived as an optimization problem wherein the stated constraints will become objective functions. The minimisation of objective functions through an iterative process leads to successful set of optimal controller parameters. In this context, Genetic Algorithm – one of the soft computing techniques used for optimisation problems - is chosen to obtain the optimal controller parameters.

4.3 GENETIC ALGORITHMS

Genetic algorithm is one of the optimization technique that uses the principles of evolution, genetics from natural biological systems. It performs a parallel, stochastic but direct search method to evolve the fittest population. Genetic algorithms are highly used in industrial process because of the following advantages (David E. Goldberg 2000).

(i) It is simple, easy to understand and implement
(ii) GA is a nonlinear process that it can be applied to most industrial processes with good performance
(iii) GA uses searching a population of points instead of searching a single solution
(iv) GA needs to know the system information only for the fitness function.
The algorithm for genetic algorithm are as follows:

Step 1 Random population of n chromosomes are initialised (optimal solutions for the problem)
Step 2 The fitness $f(x)$ of each chromosome $x$ in the population are evaluated
Step 3 A new population is created by repeating following steps until the new population is complete
Step 4 Two parent chromosomes are selected from a population according to their fitness (the better fitness, the bigger chance to get selected).
Step 5 Cross over the parents with a crossover probability to form new offspring (children). If no crossover was performed, offspring is the exact copy of parents.
Step 6 Mutate new offspring with a mutation probability at each locus (position in chromosome)
Step 7 Place new offspring in the new population
Step 8 Use new generated population for a further sum of the algorithm.
Step 9 If the end condition is satisfied, stop, and return the best solution in current population.
Step 10 Go to step 2 for fitness evaluation

4.4 GENETIC ALGORITHM BASED PID FILTER CONTROLLER FOR OPTIMALLY MEETING THE PERFORMANCE REQUIREMENTS OF ALSTOM GASIFIER CHALLENGE PROBLEMS”

Any optimisation problem aims at achieving the objectives stated in the problem. Here the objectives are: For different disturbances (load changes, grid frequency changes and fuel calorific value changes), the controlled process parameters should reach the set points with overshoots and undershoots lying within the stated values. Further the control signals should be such that the rate of variation of input signals also should not exceed the specified limits.
These objectives – quite often referred as specified constraints in the present thesis (in line with other researchers) - are to be met by proper tuning of PID controllers. Hence the optimization involved in the present study is to obtain proper Kp, Ki and Kd coefficients which will ensure above stated objectives. PIDF controllers are mostly used in all industrial processes because of its well-known beneficial features like easy implementation, low cost and its robustness. In general, the performance of the system strongly depends on the controller’s efficiency and hence tuning the PIDF parameters plays an important role in system behaviour. In this thesis, the PIDF parameters Kp, Ki, KD and N are tuned using genetic algorithm.

4.4.1 Problem formulation for Gasifier control

PID tuning can be performed using techniques like empirical methods such as Zeigler Nicholas method (O’Dwyer 2009) analytical methods like root locus technique (Nise 2006) and optimisation methods such as Lopez and Ciancone methods (Ogata 2003). The PID values obtained through these methods can be applied to a system operating in a particular operating point. When the system is operating under different operating zones, Genetic algorithms can be used to tune PID parameters taking all non-linearity and process characteristics into account.

4.4.2 Objective function for pressure and coal quality disturbance

For the proposed PID filter controller, step disturbance in PSink is applied to closed loop system and IAE (Integral Absolute errors) are calculated for over 300 seconds.

The objective functions for step and sine disturbance in Psink is given in equation (4.2) and (4.2).

\[
f_1(x)_{\text{step}} = \sum_{j=1}^{3} \sum_{i=1}^{4} \int_{0}^{300} |y_{i_{\text{isp}}}^j(t) - y_{i_{\text{isp}}}^j(t)|
\]

\[
f_2(x)_{\text{sine}} = \sum_{j=1}^{3} \sum_{i=1}^{4} \int_{0}^{300} |y_{i_{\text{isp}}}^j(t) - y_{i_{\text{isp}}}^j(t)|
\]
Similarly the objective function for coal quality change in equation in equation (4.4).

\[ f_3(x)_{\text{CV of coal}} = \sum_{i=1}^{3} \sum_{j=1}^{4} \int_{0}^{300} |y_{isp}^j(t) - y_{i}^j(t)| \]  

(4.4)

where

- \( f_1(x)_{\text{step}} \) is the objective function for step disturbance of -0.2 bar applied at Psink
- \( f_2(x)_{\text{sine}} \) is the objective function of sinusoidal disturbance of amplitude 0.2 bar and 0.04Hz frequency applied at Psink.
- \( f_3(x)_{\text{CV of coal}} \) is the objective function for disturbance at fuel fed-in.

\( y_{isp}^j(t) \) is the steady state value for output number i at operating load.

- i=1 means CV of syngas; i=2 means bedmass output; i=3 means pressure output of the syngas; i=4 means temperature output for syngas; j=1 means 100% load;
- j=2 means 50% load and j=3 means 0% load.

\( y_{i}^j(t) \) is measured output value at the three operating loads.

Combining equations (4.2), (4.3) and (4.4), the fitness value D(x) can be obtained as given in equation (4.5)

\[ D(x) = f_1(x)_{\text{step}} + f_2(x)_{\text{sine}} + f_3(x)_{\text{CV of coal}}. \]  

(4.5)

It is necessary to minimise D(X).

4.4.3 Objective function for output constraints

When the disturbances are applied, the controller must be tuned in such a way that output limits should not exceed. How well the controller meets the output constraints are given in equation (4.6) and (4.7)

\[ C_{\text{step}} = \frac{\max \max_i ||y_{i}^j - y_{isp}^j||}{D_i}, \]  

(4.6)

\[ C_{\text{sine}} = \frac{\max \max_j ||y_{i}^j - y_{isp}^j||}{D_i}, \]  

(4.7)

Where \( y_{i}^j \) = measured variable for output i at operating point j

\( y_{isp}^j \) = steady state value for output i at operating point j.

\( D_i \) = allowable deviation of output i
Combining equation (4.6) and (4.7), the output objective is given by

\[ O = \max(C_{\text{step}}, C_{\text{sine}}) \]

Therefore, the overall objective function is to minimise \( D(x) \) if \( O < 1 \).

The procedure for optimising PID filter controller with genetic algorithm is given below:

**Step 1**  The PID tuning parameters (P, I, D) must be encoded in real numbers or vectors or binary strings

**Step 2**  Population size and limits are noted

**Step 3**  Normalised Geometric selection is applied to select any random values of parameters based on fitness value.

**Step 4**  Reproduce the selected parameters to get optimised solution.

**Step 5**  Arithmetic crossover and uniform mutation are performed to alter the parameters to optimised values.

**Step 6**  Calculate the fitness value \( D(x) \) for each iteration

**Step 7**  Repeat steps 8-10 for ‘n’ off springs

**Step 8**  Using fitness function, find value of error in the Generation.

**Step 9**  The parameters with highest fitness value are chosen as the final parameter values.

**Step 10**  If the obtained values are not up to the mark, repeat step 2.

The flowchart for GA based PIDF Controller is given in Figure 4.3. Simulation results are performed in MATLAB. The number of the generations are chosen as 100. The parameter ranges of GA-PIDF controller are \( K_p \in [0 10] \), \( K_i \in [0 0.1] \), \( K_d \in [0 0.01] \) and \( N \in [2 100] \). The mutation range and cross over rate are taken as 0.5 and 0.8 respectively.

The implementation of GA based PIDF controller for Gasifier control is shown in Figure 4.4.
Figure 4.3 Flowchart representing optimization of PIDF controller using genetic algorithms for syngas pressure

\[ IAE = \int_{0}^{300} |PGAS\ setpoint - PGAS\ measured| \]
Figure 4.4 Closed loop structure for gasifier LOM with optimized PIDF control
where
G11 - transfer function characteristics between Char extraction flow rate and calorific value of syngas.
G21 - transfer function characteristics between Air flow rate and Calorific value of syngas.
G31 - transfer function characteristics between coal flow rate and Calorific value of syngas.
G41 - transfer function characteristics between steam flow rate and Calorific value of syngas.
G12 - transfer function characteristics between Char extraction flow rate and bedmass.
G22 - transfer function characteristics between Air flow rate and bedmass.
G32 - transfer function characteristics between coal flow rate and bedmass.
G42 - transfer function characteristics between steam flow rate and bedmass.
G13 - transfer function characteristics between Char extraction flow rate and pressure of syngas.
G23 - transfer function characteristics between Air flow rate and pressure of syngas.
G33 - transfer function characteristics between coal flow rate and pressure of syngas.
G43 - transfer function characteristics between steam flow rate and pressure of syngas.
G14 - transfer function characteristics between Char extraction flow rate and temperature of syngas.
G24 - transfer function characteristics between Air flow rate and temperature of syngas.
G34 - transfer function characteristics between coal flow rate and temperature of syngas.
G44 - transfer function characteristics between steam flow rate and temperature of syngas.
Also adequate care has been taken to satisfy the input constraints by using a signal limiter and a signal rate limiter. Table 4.1 shows the PIDF parameter values optimized by GA for different control loops.

Table 4.1 Proportional-Integral-Derivative-Filter parameter values for different loops obtained through genetic algorithm

<table>
<thead>
<tr>
<th>Output variables</th>
<th>Kp</th>
<th>Ki</th>
<th>KD</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVGAS</td>
<td>-0.002098</td>
<td>0.000362</td>
<td>0.01</td>
<td>100</td>
</tr>
<tr>
<td>MASS</td>
<td>0.000260</td>
<td>0.000147</td>
<td>0.2163021</td>
<td>100</td>
</tr>
<tr>
<td>PGAS</td>
<td>0.000189</td>
<td>0.000011</td>
<td>0.00001</td>
<td>0.03211</td>
</tr>
<tr>
<td>TGAS</td>
<td>1.724918</td>
<td>0.009927</td>
<td>0.151923</td>
<td>0.001574</td>
</tr>
</tbody>
</table>

4.4 PERFORMANCE TESTS

The tests such as pressure disturbance, load change and coal variation are conducted to verify the performance of the designed controller. The requirement is that the response should meet the constraints (Table 2.1 and 2.2) at 0%, 50% and 100% operating points during the performance tests, good output tracking during load change test and wide coal quality variations during coal quality test.

4.5.1 Pressure Disturbance Test

(i) Step disturbance test

At 100% load, a step change of -0.2 bar in PSink disturbance is applied at 30 second to the gasifier and the dynamic response is investigated. It is observed that all the outputs meet the performance requirements comfortably. Similarly the gasifier is initialised with 50% and 0% load conditions and the response is investigated. Figure 4.5 and Figure 4.6 shows the response of the outputs and inputs of the gasifier respectively during step change in PSink for 0%, 50% and 100% load conditions. All the outputs and input variables meet the performance requirements comfortably at all operating conditions. The peak overshoots and undershoots are within the acceptable limits for all the disturbance scenarios (D1 to D3 tests).
Figure 4.5 Closed loop response of output variables (a, b, c, d) for step disturbance at load side during 0%, 50% and 100% loads (D1, D2 and D3 tests)
Figure 4.6 Closed loop response of input variables (a, b, c, d) for step disturbance at load side during 0%, 50% and 100% loads (D1, D2 and D3 tests)
In Figure 4.5 and in Figure 4.6, the blue dashed line indicates 0% load, green solid line indicates 50% operating load and black shaded line indicates 100% load.

In Figure 4.5, (a) represents the closed loop response of output variable – CVGAS- for step disturbance at load side during 0%, 50% and 100% loads. (b) represents the closed loop response of output variable – Bedmass- for step disturbance at load side during 0%, 50% and 100% loads. (c) represents the closed loop response of output variable – PGAS- for step disturbance at load side during 0%, 50% and 100% loads. (d) represents the closed loop response of output variable – TGAS- for step disturbance at load side during 0%, 50% and 100% loads.

In Figure 4.6, (a) represents the closed loop response of input variable – Char extraction flow rate- for step disturbance at load side during 0%, 50% and 100% loads. (b) represents the closed loop response of input variable – air flow rate - for step disturbance at load side during 0%, 50% and 100% loads. (c) represents the closed loop response of input variable – coal flow rate - for step disturbance at load side during 0%, 50% and 100% loads. (d) represents the closed loop response of input variable – steam flow rate - for step disturbance at load side during 0%, 50% and 100% loads.

(ii) Sinusoidal Disturbance

The above procedure is repeated for sinusoidal PSink disturbance at all load conditions. Figure 4.7 shows the output response of gasifier at 0%, 50% and 100% loads during sinusoidal PSink disturbance. All the output (Figure 4.7) and input variables (Figure 4.8) satisfy the performance requirements. The peak overshots and undershoots of all the outputs and input variables lies within the acceptable limits (D4 to D6 tests). In Figure 4.6 and figure 4.7, the blue line represents 0% load, green line represents 50% load and black line represents 100% operating load.
In Figure 4.7 (a) represents the closed loop response of output variable – CVGAS- for sinusoidal disturbance at load side during 0%, 50% and 100% loads. (b) represents the closed loop response of output variable – Bedmass- for sinusoidal disturbance at load side during 0%, 50% and 100% loads. (c) represents the closed loop response of output variable – PGAS- for sinusoidal disturbance at load side during 0%, 50% and 100% loads. (d) represents the closed loop response of output variable – TGAS- for sinusoidal disturbance at load side during 0%, 50% and 100% loads.

In Figure 4.8, (a) represents the closed loop response of input variable – Char extraction flow rate- for sinusoidal disturbance at load side during 0%, 50% and 100% loads. (b) represents the closed loop response of input variable – air flow rate - for sinusoidal disturbance at load side during 0%, 50% and 100% loads. (c) represents the closed loop response of input variable – coal flow rate - for sinusoidal disturbance at load side during 0%, 50% and 100% loads. (d) represents the closed loop response of input variable – steam flow rate - for sinusoidal disturbance at load side during 0%, 50% and 100% loads.
Figure 4.7 Closed loop response of output variables (a, b, c, d) for sinusoidal disturbance at load side during 0%, 50% and 100% loads (D4, D5, D6 tests)
Figure 4.8 Closed loop response of input variables for sinusoidal disturbance at load side during 0%, 50% and 100% loads (D4, D5 and D6 tests)
The overshoot and undershoot values of output variables are obtained and its comparison with allowable limits during step and sinusoidal pressure disturbance are shown in Table 4.2. Table 4.2 shows all the output variables are within the allowable limits.

**Table 4.2** Comparison of overshoot and undershoot values for output variables against their allowable limiting values during pressure disturbance test with LOM

| Test Description | Outputs | Max(|y|) | Min(|y|) |
|------------------|---------|---------|---------|
|                   |         | Allowed | Obtained | Allowed | Obtained |
| 100% load, Step  | CVGAS(MJ/kg) | 4.37 | 4.3648 | 4.35 | 4.3551 |
| change in PSink | MASS(kg) | 10500 | 10000.072 | 9500 | 9999.068 |
|                  | PGAS(bar) | 20.1 | 19.981 | 19.9 | 19.9248 |
|                  | TGAS(K) | 1224.2 | 1223.211 | 1222.2 | 1222.631 |
| 50% load, Step   | CVGAS(MJ/kg) | 4.50 | 4.4961 | 4.48 | 4.4852 |
| change in PSink | MASS(kg) | 10500 | 10000.02 | 9500 | 9999.072 |
|                  | PGAS(bar) | 15.6 | 15.4882 | 15.4 | 15.4311 |
|                  | TGAS(K) | 1182.1 | 1181.132 | 1180.1 | 1180.502 |
| 0% load, Step    | CVGAS(MJ/kg) | 4.72 | 4.7198 | 4.70 | 4.7051 |
| change in PSink | MASS(kg) | 10500 | 10000.012 | 9500 | 9999.873 |
|                  | PGAS(bar) | 11.3 | 11.2018 | 11.1 | 11.1314 |
|                  | TGAS(K) | 1116.1 | 1115.147 | 1114.1 | 1114.482 |
| 100% load,      | CVGAS(MJ/kg) | 4.37 | 4.3617 | 4.35 | 4.3583 |
| Sinusoidal change| MASS(kg) | 10500 | 10000.012 | 9500 | 9999.9873 |
| in PSink        | PGAS(bar) | 20.1 | 20.076 | 19.9 | 19.898 |
|                  | TGAS(K) | 1224.2 | 1223.417 | 1222.2 | 1222.985 |
| 50% load,      | CVGAS(MJ/kg) | 4.50 | 4.4918 | 4.48 | 4.4882 |
| Sinusoidal change| MASS(kg) | 10500 | 10000.012 | 9500 | 9999.9873 |
| in PSink        | PGAS(bar) | 15.6 | 15.559 | 15.4 | 15.441 |
|                  | TGAS(K) | 1182.1 | 1181.229 | 1180.1 | 1180.729 |
| 0% load,      | CVGAS(MJ/kg) | 4.72 | 4.7212 | 4.70 | 4.7188 |
| Sinusoidal change| MASS(kg) | 10500 | 10000.012 | 9500 | 9999.967 |
| change in PSink | PGAS(bar) | 11.3 | 11.262 | 11.1 | 11.138 |
|                  | TGAS(K) | 1116.1 | 1115.892 | 1114.1 | 1114.108 |
The maximum flow rates and rate of change of flow rates obtained for different input variables are obtained and Table 4.3 shows the comparison of these values with their allowable limiting values and it has been found that all the input variables are within the tolerable rates and limits.

Table 4.3 Comparison of maximum flow rates and rate of change of flow rates obtained for different input variables (Pressure disturbance test) with LOM

<table>
<thead>
<tr>
<th>Test Description</th>
<th>Outputs</th>
<th>Maximum value in Kg s$^{-1}$</th>
<th>Minimum value in Kg s$^{-1}$</th>
<th>Rate (Kg s$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% load, Step change in PSink</td>
<td>WCHR</td>
<td>1.928</td>
<td>0.828</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>WAIR</td>
<td>9.92</td>
<td>17.892</td>
<td>0.783</td>
</tr>
<tr>
<td></td>
<td>WCOL</td>
<td>9.828</td>
<td>8.628</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>WSTM</td>
<td>3.529</td>
<td>2.786</td>
<td>1.0</td>
</tr>
<tr>
<td>50% load, Step change in PSink</td>
<td>WCHR</td>
<td>1.898</td>
<td>0.792</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>WAIR</td>
<td>10.872</td>
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<td></td>
<td>WCOL</td>
<td>7.172</td>
<td>5.328</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>WSTM</td>
<td>3.138</td>
<td>1.821</td>
<td>1.0</td>
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<tr>
<td>0% load, Step change in PSink</td>
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<td>0.511</td>
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<td></td>
<td>WCOL</td>
<td>3.813</td>
<td>2.131</td>
<td>0.2</td>
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<td></td>
<td>WSTM</td>
<td>2.131</td>
<td>0.811</td>
<td>1.0</td>
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<td>100% load, Sinusoidal change in PSink</td>
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<td>9.64</td>
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<td></td>
<td>WCOL</td>
<td>6.35</td>
<td>4.33</td>
<td>0.193</td>
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<tr>
<td></td>
<td>WSTM</td>
<td>1.856</td>
<td>1.524</td>
<td>0.793</td>
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<td>50% load, Sinusoidal change in PSink</td>
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<td>0.686</td>
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<td>WAIR</td>
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<td></td>
<td>WCOL</td>
<td>9.832</td>
<td>7.418</td>
<td>0.192</td>
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<td></td>
<td>WSTM</td>
<td>2.896</td>
<td>2.504</td>
<td>0.884</td>
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<td>0% load, Sinusoidal change in PSink</td>
<td>WCHR</td>
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<td>0.355</td>
<td>0.2</td>
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</tr>
<tr>
<td></td>
<td>WCOL</td>
<td>3.248</td>
<td>1.024</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>WSTM</td>
<td>0.855</td>
<td>0.497</td>
<td>0.996</td>
</tr>
</tbody>
</table>

Also it is observed that the performance violation found in PGAS with sinusoidal disturbance in PGAS for baseline PI controller (Dixon 2006) is
suitably corrected by proposed GA based PIDF Controller. Thus the proposed GA based PIDF Controller are able to meet all the performance requirement stated in ALSTOM challenge I.

### 4.5.2 Load change test

Load change test is conducted to verify the stability of the Gasifier and controller function across the working range of the plant.

![Closed loop response of output variables for Load ramping from 50% load to 100% load using LOM](image)

Figure 4.9 Closed loop response of output variables for Load ramping from 50% load to 100% load using LOM
The system is started at 50% load in steady state and ramped it to 100% over a period of 800 seconds (5% per minute) and the response is recorded for 80 minutes. Figure 4.9 and Figure 4.10 shows the input and output response of the gasifier to load change from 50% to 100%.

Figure 4.10 Closed loop response of input variables for Load ramping from 50% load to 100% load using LOM
It is seen that the actual load, CVGAS and PGAS track their demands quickly to set point while bedmass takes more time to reach its steady state, though manipulated inputs coal flow and char flow have reached their steady state immediately.

4.5.3 Coal Quality Variation Test

Carbon content and moisture content of the coal decides the quality of coal gas. Usually the coal quality is not constant over a period of time and may vary to a considerable amount. The performance of proposed PIDF controller during coupled disturbance in Psink (output side of gasifier) and change in Calorific Value of coal (input side of Gasifier) are investigated.

For this purpose, the Gasifier is initialised with 100% load condition and subjected to a step change in PSink at 30 seconds. Then coal quality change (+18%) is introduced at 100 seconds. The response is observed for 300 seconds and any deviation from the desired performance is investigated. The same procedure is repeated for 100% with -18% changes in coal quality variations coupled with step disturbance.

Figure 4.11 shows the output responses of the coal gasifier at 100% during step disturbances in PSink coupled with ±18% of coal quality variations. It is observed that all the output variables are within the tolerable limits and meet the performance requirements. In Figure 4.11, (a) represents the closed loop response of output variable –CVGAS, (b) represents the closed loop response of output variable - Bedmass, (c) represents the closed loop response of output variable- PGAS, (d) represents the closed loop response of output variable – TGAS for step disturbance at load side with ±18% CV of coal quality at 100% load.
Figure 4.12 shows the input responses of the coal Gasifier at 100% during step disturbances in PSink coupled with ±18% of coal quality variations. It is observed that all the input variables are within the tolerable limits and also within the tolerable rates and thus meeting all the performance requirements. In Figure 4.12, (a) represents the closed loop response of input variable – char extraction flow rate (b) represents the closed loop response of input variable - air flow rate, (c) represents the closed loop response of input variable- coal flow rate (d) represents the closed loop response of input variable – char extraction flow rate for step disturbance at load side with ±18% CV of coal quality at 100% load.

Similar tests are conducted for 50% and 0% load. Figure 4.13 shows the output response of gasifier with step disturbance in Psink for 50% load.

It is observed that all the output variables and input variables are within the tolerable limits and meet the performance requirements and the gasifier performs well even with maximum allowable coal quality variations.
Figure 4.11 Closed loop response of output response for step disturbance at load side coupled with ±18% CV of coal quality at 100% load
Figure 4.12 Closed loop response of Input response for step disturbance at load side coupled with ±18% CV of coal quality at 100% load
Figure 4.13 Closed loop response of output response for sinusoidal disturbance at load side coupled with ±18% CV of coal quality at 50% load
Figure 4.14 shows the input response at 50% load during step change in PSink coupled with ±18% of coal quality variations. All the input variable meets the performance requirements without violating the constraints. It is worthwhile to point out that some of the output variables like temperature and pressure are not meeting the constraints in the earlier approaches.

Figure 4.15 and figure 4.16 shows the response at 0% load during step change in PSink coupled with ±18% of coal quality variations. All the input and outputs meets the performance requirements without violating the constraints. The gasifier performs well even with maximum allowable coal quality variations.

Similarly the Gasifier is tested with sinusoidal disturbance at the output side. For this purpose, the Gasifier is initialised with 100% load condition and subjected to a sinusoidal change in PSink, then coal quality change (+18%) is introduced at 100 seconds. The response is observed for 300 seconds and any deviation from the desired performance is investigated. The same procedure is repeated for 100% with -18% changes in coal quality variations.

Figure 4.17 and Figure 4.18 shows the output and input responses of the coal gasifier at 100% during sinusoidal disturbances in PSink coupled with ±18% of coal quality variations.
Figure 4.14 Closed loop response of input response for sinusoidal disturbance at load side coupled with ±18% CV of coal quality at 50% load
Figure 4.15 Closed loop response of output response for step disturbance at load side coupled with ±18% CV of coal quality at 0% load
Figure 4.16 Closed loop response of input response for step disturbance at load side coupled with ±18% CV of coal quality at 0% load
Figure 4.17 Closed loop response of output response for sinusoidal disturbance at load side coupled with ±18% CV of coal quality at 100% load.
Figure 4.18 Closed loop response of input response for sinusoidal disturbance at load side coupled with ±18% CV of coal quality at 100% load
It is observed that all the input and output variables are within the tolerable limits except TGAS reaches its allowable limit during -18%, which is considered as performance violation.

Similar tests are conducted for 50% and 0% operating loads. Figure 4.19 and Figure 4.20 shows the output and input responses of the coal gasifier at 50% during sinusoidal disturbances in PSink coupled with ±18% of coal quality variations. It is observed that all the input and output variables are within the tolerable limits. Figure 4.21 and Figure 4.22 shows the output and input responses of the coal gasifier at 0% during sinusoidal disturbances in PSink coupled with ±18% of coal quality variations.

It is observed that all the input and output variables are within the tolerable limits except WCHR (char extraction flow rate), and WSTM (steam flow rate) reaches its lower limit during -18% change in coal quality, which is considered as performance violation.

TGAS violate the limits under coal quality change for sinusoidal pressure disturbance and no output variable is found for step pressure disturbance.

The results obtained in the present investigation meets challenge requirement I and II to the greatest extent as can be seen from Table 4.4 (present work) and Table 2.3 (the summary of earlier results)
Figure 4.19 Closed loop response of output response for sinusoidal disturbance at load side couple with ±18% CV of coal quality at 50% load
Figure 4.20 Closed loop response of input response for sinusoidal disturbance at load side coupled with ±18% CV of coal quality at 50% load.

(a) Char extraction Vs Time
(b) Air Vs Time
(c) Coal Vs Time
(d) Steam Vs Time
Figure 4.21 Closed loop response of output response for sinusoidal disturbance at load side coupled with ±18% CV of coal quality at 0% load.
Figure 4.22 Closed loop response of input response for sinusoidal disturbance at load side coupled with ±18% CV of coal quality at 0% load
Table 4.4 shows the violation of the variables under positive (+18%) and negative change (-18%) in coal quality. Since input constraints are inbuilt in the actuator limits, output constraints are considered to be the actual violation.

Table 4.4 Summary of input and output variables either meeting or not meeting the constraints in closed loop mode for different disturbances with LOM

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Variables</th>
<th>Disturbances for which control requirements have been met are indicated by √ while ‘x’ indicates partial fulfilment of control requirements.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>D1</td>
</tr>
<tr>
<td>1</td>
<td>CVGAS</td>
<td>√</td>
</tr>
<tr>
<td>2</td>
<td>MASS</td>
<td>√</td>
</tr>
<tr>
<td>3</td>
<td>PGAS</td>
<td>√</td>
</tr>
<tr>
<td>4</td>
<td>TGAS</td>
<td>√</td>
</tr>
<tr>
<td>5</td>
<td>WCHR</td>
<td>√</td>
</tr>
<tr>
<td>6</td>
<td>WAIR</td>
<td>√</td>
</tr>
<tr>
<td>7</td>
<td>WCOAL</td>
<td>√</td>
</tr>
<tr>
<td>8</td>
<td>WSTM</td>
<td>√</td>
</tr>
</tbody>
</table>
4.6 CONCLUSION

It is observed that PIDF controllers whose parameters ($K_p$, $K_i$ and $K_d$) had been evaluated using genetic algorithm ensured the performance requirement fully as dictated in Challenge – I problem.

The Challenge – II requires the controller to meet the performance requirement during simultaneous disturbances occurring at both output (load) side and input (change in calorific value). It is to be noted that while the researchers have fully solved challenge I problem, the efforts of researchers have been found to be providing incremental improvement in satisfying challenge II problem.

In the present investigation, it is observed that significant results have been achieved in the sense that the percentage of performance requirement (the plus or minus percentage variation of CV of coal with respect to design value) met is more compared to published results.

However being daunted by a question: could the results obtained by LOM route be compared with those with original higher order model, a fresh simulation studies had been carried with the original higher order model coupled with PIDF controller in chapter 5 for further understanding and analysis.