CHAPTER 2

LITERATURE REVIEW

In India, about 60 percent of commercial energy requirement is met by fossil fuel like coal. Coal can be a substitute for power generation as oil and gas reservoirs are depleting. But, utilization of coal has increased environmental pollutions such as carbon dioxide, Nitrogen Oxides (NOx) and Sulphur Oxides (SOx) and particulate disposal. With most Indian thermal power plants, more carbon is burnt for generation of each unit of electricity causing a higher value of CO₂/kWh. If this conventional fossil technology continues for next 25 years, the annual CO₂ likely to be emitted into atmosphere due to power generation in the year 2025 will increase fourfold from the present level (Bansal and Hake, 2000). Hence, setting up of new power plants are broadly based on environment friendliness and more efficient operation. In this context, the Integrated Gasification Combined Cycle (IGCC) operation is becoming popular to burn abundantly available coal.

2.1 COAL GASIFICATION

Gasification technology which had its beginning in the late 1700s was mostly used for the generation of “town gas” during 19th century. Unfortunately, it lost its ground during 20th century due to widespread availability of natural gas (Ramezan and Stiegel, 2006). IGCC technology is gaining popularity among power producers for the following reasons:

- 10% more efficient than conventional power generation
- Prohibitive high cost of power generation through IGCC is, in fact, becoming cheaper than pulverized coal plant if one considers the cost of carbon capture and sequestration
Today, the Gasification technology is being widely attempted throughout the world. In USA, 262 MW Wabash River IGCC power plants in Indiana (later acquired by Conoco Philips), 250MW Polk Power Station IGCC in Tampa, Florida (later acquired by GE Energy) and 160 MW Edwardsport IGCC in Indiana, Kemper County IGCC in Mississippi are the three notable commercial IGCC coal based power plants under operation. Although, IGCC power plants are being put up worldwide sporadically, 300 MW KOWEPO project in South Korea, 250MW IGCC demonstration plant in Tianjin (China) and 125 MW IGCC plant at Vijayawada (India) seem to be the potential demonstration plants in Asian region.

Even though a number of IGCC projects exist, the UK’s Clean Coal Power Generation Group (CCPGG), 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 87 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. Technically, an IGCC consists of a Gasifier (which converts solid coal fuel into a gaseous fuel) and the Combined Cycle Operating plant (CCP). In other words, the gas turbine of CCP is to be fed with gaseous fuel known as syngas produced through gasification process instead of natural gases hitherto fed into the turbine. A brief account of different types of Gasifier is covered in the next section.

2.2 TYPES OF GASIFIER

Generally, Gasifier are classified into three types according to their flow geometry (Phillips et al. 2006).

2.2.1 Fixed bed Gasifier

Figure 2.1 shows the moving bed gasifier where coal enters at the top of the reactor and air or oxygen enters at the bottom. As the coal moves slowly
down the reactor, solid fuel is converted into gaseous fuel because of kinetic chemical reactions. The ash present in the coal are collected at the bottom of the reactor. Example: British Gas Lurgi (BGL), Lurgi (Dry Ash).

Figure 2.1 Schematic diagram of Moving bed Gasifier

2.2.2 Entrained Flow Gasifier

Texaco, EGas, Mitsubishi power plants have Entrained flow Gasifier. These type of Gasifier uses oxygen rather than air. Here 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. Figure 2.2 shows Entrained flow gasifier.

Figure 2.2 Schematic diagram of Entrained Flow Gasifier
2.2.3 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, IGT “UGas” and ALSTOM gasifier.

Figure 2.3 Schematic diagram of Fluidized bed Gasifier

2.3 AIR BLOWN GASIFICATION CYCLE (ABGC)

An industry led consortium named Clean Coal Power Generation Group was set up in order to continue the coal based power generation in the year 1993. The consortium was led by GEC ALSTHOM, represented by European Gas Turbines Ltd (EGT). Mitsui Babcock Energy Ltd, Powergen PLC and the Coal Technology Development Division of the British Coal Corporation were also the members of this consortium. The programme primarily addressed the development of Prototype Integrated Plant called Air Blown Gasification Cycle (ABGC). The ABGC is a clean coal technology developed to provide
environmentally clean and efficient power generation from a range of non-premium fuels. The ABGC has the power generation capacity of 87 MW. ABGC consists of gasifier, boost compressor, steam turbine and gas turbine. Coal, steam and air react in the gasifier – which operates at approximately 22 bar, 1150 K - to produce low calorific value fuel gas for combustion in a gas turbine. The gas turbine is further coupled with generator to generate power. The exhaust heat from gas turbine are given to steam turbine – generator circuit to produce additional power. All the required gas and steam cycle component models were developed, tested and validated prior to integration to produce the complete Prototype Integrated Plant (PIP) model (Liu et al. 2000). Controlling the PIP is not normally encountered in conventional power plants. The key elements of the plant are the Gasifier, the gas turbine which runs on low calorific fuel-gas, the CFBC and the global plant control itself. The control system analysis are aimed at

(i) Verify the PIP model such that the plant can be safely and adequately controlled.
(ii) To examine some of the more complex components of the PIP – Gasifier - in order to propose safer, more economical, higher performance controllers using advanced control techniques.

Exhaustive simulation case studies were conducted in order to demonstrate the effectiveness of the proposed PIP control scheme. These control scheme was shown to be capable of controlling the complete plant in three operating loads namely full load (100% load), half load (50% load) and no-load (0% load). Out of which, 0% load is found to be severe to control.

2.4 CHEMISTRY BEHIND GASIFIER

ALSTOM Gasifier model is the most complex model which was started in the year 1992 by CRE Group Limited. In 1994, the model development
was continued at the GEC ALSTHOM Mechanical Engineering Centre. The gasifier is a reactor where incoming coal is dried and devolatilised to yield char, ash and volatile gases. Oxygen in air reacts with carbon to form carbon dioxide and carbon mono oxide. Limestone is added to capture sulphur in coal. Both exothermic and endothermic reactions occur.

\[
\begin{align*}
C + O_2 & \rightarrow CO_2&(2.1) \\
C + \frac{1}{2} O_2 & \rightarrow CO&(2.2) \\
C + CO_2 & \rightarrow 2CO&(2.3) \\
C + H_2O & \rightarrow CO + H_2&(2.4)
\end{align*}
\]

Equation (2.1) and equation (2.2) are exothermic reactions which yields carbon dioxide and carbon monoxide. Equation (2.3) and (2.4) are endothermic reactions where carbon dioxide reacts with more carbon to form carbon monoxide and steam reacts with carbon to from carbon monoxide and hydrogen.

The unreacted carbon are added to a bed which is maintained at a constant height by a char extraction system. The composition and temperature of the fuel gas and char are calculated by the mass and heat balance equations. Figure 2.4 shows the chemistry of Gasifier. The system involves many complicated chemical reactions with large time constant and interactions among the control loop thus making the Gasifier, a highly coupled system.
2.5 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 2006). Figure 2.5 shows the input and output variables of Gasifier.
The controllable input variables to the gasifier are

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

The Controlled output variables are:

- Gas calorific value (y1) \(\text{CVGAS(J/Kg)}\)
- Bed mass (y2) \(\text{MASS(Kg)}\)
- Fuel gas pressure (y3) \(\text{PGAS(N/m}^2\) )
- Fuel gas temperature (y4) \(\text{TGAS(K)}\)

One of the inputs, limestone mass \(\text{WLS}\) 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 \(\text{WCOL}\). This leaves effectively 4 degrees of freedom for the control design.

2.6 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 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 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.

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 for ready reference. Table 2.1 shows the steady state values for input variables for different operating loads.

Table 2.1 Input Variables and their limits

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
<th>Maximum Value</th>
<th>Rate</th>
<th>Steady state values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>WCHR(Kg/s)</td>
<td>Char extraction flow rate</td>
<td>3.5</td>
<td>0.2 Kg/s²</td>
<td>0.9</td>
</tr>
<tr>
<td>WAIR (Kg/s)</td>
<td>Air flow rate</td>
<td>20</td>
<td>1.0 Kg/s²</td>
<td>17.42</td>
</tr>
<tr>
<td>WCOL(Kg/s)</td>
<td>Coal flow rate</td>
<td>10</td>
<td>0.2Kg/s²</td>
<td>8.55</td>
</tr>
<tr>
<td>WSTM(Kg/s)</td>
<td>Steam flow rate</td>
<td>6.0</td>
<td>1.0Kg/s²</td>
<td>2.70</td>
</tr>
<tr>
<td>WLS(Kg/s)</td>
<td>Limestone flow rate</td>
<td>1.0</td>
<td>0.02Kg/s²</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Table 2.2 shows the steady state values and allowable fluctuations for output variables.

Table 2.2 Output variables and their limits

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Description</th>
<th>Allowed fluctuations</th>
<th>Steady state values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>CVGAS(MJ/Kg)</td>
<td>Fuel gas calorific value</td>
<td>± 0.01</td>
<td>4.36</td>
</tr>
<tr>
<td>MASS(Kg)</td>
<td>Bedmass</td>
<td>± 500</td>
<td>10000</td>
</tr>
<tr>
<td>PGAS(N/m²)</td>
<td>Fuel gas pressure</td>
<td>±1 x 10⁴</td>
<td>2 x 10⁶</td>
</tr>
<tr>
<td>TGAS(K)</td>
<td>Fuel gas temperature</td>
<td>± 1.0</td>
<td>1223.2</td>
</tr>
</tbody>
</table>
2.7 ALSTOM BENCHMARK CHALLENGES

The ALSTOM gasifier is modelled in state space form given by

\[
\dot{X} = Ax + Bu \\
Y = Cx + Du
\]  

(2.5)

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 4x25
- \( D \) = disturbance matrix with dimension 4x6

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

- \( A, B, C, D \) 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](http://www.ieee.org/OnComms/PN/controlauto/benchmark.cfm)). However, for ready references these values are given in Appendix 1, for 100%, 50% and 0% loads. ALSTOM Power technology centre issued a benchmark challenge I and II to research community for gasifier model.

- 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.)
2.7.1 **FIRST CHALLENGE** (Pike et al. 1998)

The first challenge involves the evaluation of control loop performances during disturbances occurring from load side. Towards this, the simulation test to be performed are:

(i) **Pressure Disturbance test**

Disturbance 1: A sudden disturbance of pressure change at throttle value with -0.2 bar, corresponding to a step change at 100% load.

Disturbance 2: A sudden disturbance of pressure change at throttle value with -0.2 bar, corresponding to a step change at 50% load.

Disturbance 3: A sudden disturbance of pressure change at throttle value with -0.2 bar, corresponding to a step change at 0% load.

Disturbance 4: A disturbance of pressure change represented by $A \times \sin(\omega t)$ with $A= 0.2$ bar and frequency $\omega = 0.04\text{Hz}$ at the throttle valve which corresponds to low frequency movements of inlet valve representing changes in grid frequency at 100% load.

Disturbance 5: A disturbance of pressure change represented by $A \times \sin(\omega t)$ with amplitude $A= 0.2$ bar and frequency $\omega = 0.04\text{Hz}$ at the throttle valve which corresponds to low frequency movements of inlet valve representing changes in grid frequency at 50% load.

Disturbance 6: A disturbance of pressure change represented by $A \times \sin(\omega t)$ with amplitude $A= 0.2$ bar and frequency $\omega = 0.04\text{Hz}$ at the throttle valve which corresponds to low frequency movements of inlet valve representing changes in grid frequency at 0% load.

The following test case guideline should be followed

1. Initialize the plant (gasifier) model corresponding to desired operating point (say 100% Load).
2. Select the control strategy / algorithm and suitably incorporate the controller with the plant model.

3. Apply step disturbance of -0.2 bar at t=30 second and run the simulation for 300 seconds.

4. Calculate Maximum Absolute Error (MAE) during the transient period of gasifier output parameters such as calorific value (CVGAS), pressure (PGAS) and temperature (TGAS) of syngas and bed mass.

5. Evaluate the efficacy of the proposed control strategy based on the transient performance of the input /output process parameters examining the controlled output variable attains the specified set point.
   (a) Overshoots and undershoots lie within the specified limits.
   (b) Rate of variation of input variables lies within specified limits.

6. Repeat the steps 3 to 5 for all the six types of disturbances and for all operating conditions.

2.7.2 SECOND CHALLENGE

The second challenge consists of two test (Dixon and Pike 2006)

(ii) Load Change Test

Disturbance 7: Load transition: ramping up of load from 50% to 100% operating point. This test facilitates the evaluation of controller performance across the full operating range of the plant. The plant model is initialized to represent 50% load and then increased continuously to 100% load at the rate of 5% per minute.

The proposed controller should ensure the following

(a) Stability of the gasifier across the operating region.
(b) Fluctuations of the input variables should lie within the limits.
(c) The peak overshoots and undershoots at the end of the ramp input should meet the specified constraints.
(iii) Coal Quality Test

The investigation on the performance of the proposed controller during coupled disturbances, both from input and output sides of the gasifier constitute the second challenge. In other words, 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, the following types of pressure disturbance tests should be conducted along with change in calorific value of the fuel and any deviation from the desired performance is to be investigated.

Disturbance 8: A pressure disturbance represented by $A^* \sin(\omega t)$ with amplitude $A = 0.2$ bar and frequency $\omega = 0.04\text{Hz}$ at the throttle valve and simultaneously step change of 18% in calorific value over the designed calorific value of the fuel (coal) at 100% load.

Disturbance 9: A pressure disturbance represented by $A^* \sin (\omega t)$ with amplitude $A= 0.2$ bar and frequency $\omega = 0.04\text{Hz}$ at the throttle valve and simultaneously step change of 18% in calorific value over the designed calorific value of the fuel (coal) at 50% load.

Disturbance 10: A pressure disturbance represented by $A^* \sin (\omega t)$ with amplitude $A= 0.2$ bar and frequency $\omega = 0.04\text{Hz}$ at the throttle valve and simultaneously step change of 18% in calorific value over the designed calorific value of the fuel (coal) at 0% load.

Disturbance 11: A pressure disturbance represented by $A^* \sin (\omega t)$ with amplitude $A= 0.2$ bar and frequency $\omega = 0.04\text{Hz}$ at the throttle valve and simultaneously step change of 18% in calorific value under the designed calorific value of the fuel (coal) at 100% load.

Disturbance 12: A pressure disturbance represented by $A^* \sin (\omega t)$ with amplitude $A=0.2$ bar and frequency $\omega = 0.04\text{Hz}$ at the throttle valve and
simultaneously step change of 18% in calorific value under the designed calorific value of the fuel (coal) at 50% load.

Disturbance 13: A pressure disturbance represented by $A^* \sin(\omega t)$ with amplitude $A=0.2$ bar and frequency $\omega=0.04$Hz at the throttle valve and simultaneously step change of 18% in calorific value under the designed calorific value of the fuel (coal) at 0% load.

Disturbance 14: A pressure disturbance of step change of -0.2 bar at the throttle valve and simultaneously step change of 18% in calorific value under the designed calorific value of the fuel (coal) at 100% load.

Disturbance 15: A pressure disturbance of step change of -0.2 bar at the throttle valve and simultaneously step change of 18% in calorific value over and above the designed calorific value of the fuel (coal) at 50% load.

Disturbance 16: A pressure disturbance of step change of -0.2 bar at the throttle valve and simultaneously step change of 18% in calorific value over and above the designed calorific value of the fuel (coal) at 0% load.

Disturbance 17: A pressure disturbance of step change of -0.2 bar at the throttle valve and simultaneously step change of 18% in calorific value under the designed calorific value of the fuel (coal) at 100% load.

Disturbance 18: A pressure disturbance of step change of -0.2 bar at the throttle valve and simultaneously step change of 18% in calorific value under the designed calorific value of the fuel (coal) at 50% load.

Disturbance 19: A pressure disturbance of step change of -0.2 bar at the throttle valve and simultaneously step change of 18% in calorific value under the designed calorific value of the fuel (coal) at 0% load.
The maximum allowable limits for coal quality variations are ±18% with respect to the original calorific value of the coal.

### 2.8 RESEARCHERS ATTEMPT IN THE FIRST CHALLENGE

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.

Liu et al. (2000) used multivariable P and I controllers using multi-objective optimal tuning technique and model based predictive control design to meet the constraints. The specification on the outputs, inputs and input rates of the gasifier were formulated as multi-objective performance function criteria that are expressed by a set of inequalities. For 100% load, MIMO PI controller had successfully designed using multi-objective control techniques to satisfy all the specifications when the step and sinusoidal pressure disturbances were applied. The controller satisfied the performance requirement for step change in PSink disturbance while performance violation was reported with sinusoidal PSink disturbance.

Rice et al. (2000) proposed predictive control that uses linear quadratic optimal inner loop and it is supervised by an outer predictive controller loop. The aim is to illustrate the efficacy of two novel approaches to predictive control. In the first approach the system is first stabilized with a simple control law. The predictive control is then added as an outer loop optimisation for constraint handling. The second approach is computationally more efficient; here constraints are handled by a systematic mixing of two stabilising control laws. The controller satisfies all the disturbance test but failed in sinusoidal disturbance at 0% load.
Proportional integral plus (PIP) by Taylor et al. (2000) from Lancaster University was based on discrete time model of the plant. It is based on the backward shift operator reduced order model using a single uniform sampling rate, satisfying all the performance requirement at 100 and 50% load. But at 0% load, violation met for PGAS output variable during sinusoidal disturbances.

Prempain et al. (2000) demonstrated the use of loop shaping H-infinity control design method. A regulator was designed for the 100% load. It worked well for the three operating points in the presence of step disturbance. Good results were also obtained with the sine disturbance at 100% and 50% load. But at 0% load, violation met.

The multi-objective Genetic algorithm (MOGA) was proposed by Griffin et al. (2000) which performed a loop-shaping H-infinity design. A multi objective genetic algorithm is used in conjunction with an H-infinity loop shaping design procedure in order to satisfy the requirement of this critical system. It is used to guarantee the stability and robustness of the controller wherein its associated weighting matrix parameters are selected using the multi objective search method in order to achieve performance requirements. Here performance violation in PGAS was reported at 0% load with sinusoidal disturbances.

A sliding mode, nonlinear design approach was suggested by Sarah et al. (2000). Here switching surface is designed to move the plant from one operating point to the other. Neil Munro decomposed the original problem into a series of much simpler schemes in an effort to divide and conquer rule. Munro (2000) combined sequential loop closing with a high –frequency decoupling approach along with divide and conquer method. Here performance violation in PGAS was reported at 0% load with sinusoidal disturbances.
Asmer et al (2000) investigated four different control strategies based on Relative Gain Array (RGA) loop paring approach in which four SISO control schemes had been employed. This Baseline controller was implemented on Benchmark challenge which dealt with only pressure disturbance test. All the performance requirements were satisfied at 50% and 100% load conditions while, performance violation in PGAS was reported at 0% load with sinusoidal pressure disturbance.

Nobakhti et al. (2008) used self-adaptive Differential Evolution (DE) approach for optimisation of MIMO PI controllers. The optimisation techniques have a relatively high misconvergence rate that is, the algorithm is very good in locating the proximity of the global minima, but requires enormous amount of time finding it exactly. Also violation met for 0% load.

Chin et al. (2003) considered the analysis and controller design for the ALSTOM gasifier system. The inherent properties of this highly coupled multivariable system are studied. Minimal realizations of the system models at the three operating points to be considered are determined, and the numerical condition of the system is improved. Model order reduction methods are applied to simplify the subsequent design. A controller is designed using the LQG/LTR technique at the 100% load condition, and the robustness of this controller at other load conditions is assessed. No violation in the desired performance specifications was encountered during 100% load while performance violation met for 0% load.

Agustriyanto and Zhang (2009) provided a systematic analysis for evaluating the disturbance rejection performance of different control structures of ALSTOM gasifier using Generalised Relative Disturbance Gain (GRDG) technique. A linear transfer function model was obtained through Output Error (OE) algorithm and further analyses were made using GRDG method. The analysis concluded that the control structure proposed by Asmer et al (2000)
was the most favoured multi-loop control structure for ALSTOM gasifier. Investigations on pressure disturbance were done for 50% and 100% loads leaving 0% load untouched. It was indicted that RGA analysis was not suitable in selecting the control structure for this benchmark problem.

### 2.9 RESEARCHERS ATTEMPT IN 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 (Dixon 2006) and desired the controller capability during load changes and coal quality disturbance (model error tests). A group of control solutions for the benchmark problem were presented at Control-2004 Conference at Bath University, UK in September 2004.

Dixon & Pike (2006) introduced the challenge pack II to the academic community inviting solutions for gasifier control. Numerous issues concerning the modelling and control of ALSTOM benchmark Challenge II were discussed. This challenge pack was provided with Baseline PI controller along with Load test and coal quality test. Investigations at 100% and 50% load showed excellent results while PGAS violation at 0% load for sinusoidal pressure disturbance was reported. This base line controller was used by the other researchers for comparison purposes.

A state estimation-based feed forward in addition to the base-case feedback control system has been proposed by Wilson (2006) from Nottingham University. Using Kalman filter, estimation of two primary disturbances affecting the gasifier (sink pressure PSINK and coal quality CQ) are done. This approach improves on the response of the conventional SISO control system in the specified test conditions at 100% and 50% loads, whereas performance improvements at 0% load (the most testing condition) are marginal. Multi
objective optimization approach suggested by Simm and Liu (2006) from Nottingham University made further improvement by the addition of proportional control loops and violation met at 0% load.

Haryanto et al (2009) developed plant simulator that integrates MATLAB as an engine and DCS CS3000 as an industrial controller. It used lower modelling for gasifier and investigation on controller design during disturbances are not reported.

Exadaktylos et al (2009) discussed the application of PIP control methods to the ALSTOM Benchmark Challenge II. The approach is based on the identification of discrete-time TF models using the simplified refined instrumental variable (SRIV) algorithm. Here, closed loop PIP control was obtained by manual tuning. PIP controller considered here has a similar implementation complexity to conventional PI/PID designs, requiring only the addition of a multivariable structure and storage of additional past values. PIP controller are discrete time algorithm and its limitation is that takes up to one sampling interval before the controller starts to respond to a disturbance input. In simulation, this puts the approach at a disadvantage against continuous-time designs such as the multiple-loop PI algorithm.

Al Seyab & Cao (2006) suggested Nonlinear Model Predictive Control (NMPC). A nonlinear MPC controller was used to identify PGAS while a linear model load was adopted as base model for other output variables at 0% load. A multilayer feed forward neural network was used as nonlinear static element of the Wiener model. A linear internal model for PGAS was obtained by linearizing nonlinear PGAS model at every sampling time. The performance during pressure disturbance and load change were investigated leaving coal quality test untouched. The response satisfied the performance requirements comfortably to some degree without violating the input-output constraints.
Yong Wang et al (2009) explained the use of fuzzy gain scheduled controller design followed by multi-model predictive Control (DMC). This method is convenient to deal with various constraints, to solve multi-variable control problem coupled system. One of the limitation is to reduce the calculating value of multi-model predictive control. This algorithm is also applied to Alstom gasifier model and failed to satisfy the input constraints at 0% load.

Xue et al (2010) used multi-objective algorithm NSGA-II for the baseline PI controllers of ALSTOM gasifier benchmark. Non-linear gasifier model is adopted in Simulink simulation, and a set of non-dominated feasible solutions is obtained, which all satisfies the performance requirements under various pressure disturbances and load conditions with constraints not met especially at coal quality variations.

Wang Xin et al. (2010) used a nonlinear identification approach and implemented on Alstom gasifier with Wiener model. The linear element of the Wiener model is identified by a combined subspace state space method, which integrates MOESP (Multivariable Output-Error State Space) and N4SID (Numerical algorithms for subspace n state space system identification) method in the estimation of system matrices. A single layer neural network is chosen as the nonlinearity of the model. All parameters of the wiener model are optimized by Levenberg-Marquardt algorithm, using the model parameters obtained formerly as the initial estimates. A nonlinear model of the plant at 0% load is adopted as a base model for estimation. The simulation shows better results with constraints not met especially at coal quality variations.

Huang et al (2013) developed a first order Active Disturbance Rejection Control (ADRC) for ALSTOM benchmark challenge II. The disturbances (unknown dynamics, PSink change, load change and coal quality change) were estimated and eliminated in real time. The Baseline PI controller structure suggested by Asmer et al (2000) was adopted. Three first order ADRC
controllers were designed and replaced the three PI controllers of Baseline PI controller. The performance of the gasifier was investigated during pressure disturbance, load change and coal quality change which showed improved results, meeting all the performance requirements with some limit violations.

Tan et al (2011) proposed multivariable control system with strict constraints on the inputs and outputs which makes it very difficult to control. Partially decentralized controller design method are used based on the stabilizer idea. The method only requires identifying some closed-loop transfer functions and solving an H∞ optimization problem. The final partially decentralized controller is easy to implement and test in practice. Two partially decentralized controllers are designed for the ALSTOM gasifier benchmark problem, and simulation results show that they both meet the design specifications with some limit violations.

Koteeswaran et al (2013) used optimisation algorithm such as Multi-objective Particle Swarm Optimization (MOPSO) algorithm, Firefly algorithm, cuckoo algorithm, Bat algorithm are proposed to fine-tune the parameters of baseline PI controller of Alstom gasifier benchmark challenge II. MOPSO algorithm provides set of non-dominated solutions for the baseline PI controller, among which a suitable set of PI parameters are selected. The performance tests such as pressure disturbance, load change, and coal quality variations are investigated. During pressure disturbance test, the controller with optimized settings meets all the performance requirements at 0%, 50%, and 100% load conditions. Load change test shows good results. During coal quality test, the gasifier along with optimized controller settings violates the specified limits on input and output variables.

**Inference**

All the papers had achieved reasonable success in terms controlling the gasifier model. But none of the controller met the overall performance
criteria and hence the benchmark challenges keep attracting the researchers for further work.

For the purpose of comparison to what extent the ALSTOM Challenges had been satisfied by earlier researchers, ALSTOM Challenges I and II have been split into different disturbances for which simulation studies should be done. They are designated as D1 to D19 (19 simulation runs) and a brief explanation is given for each type of disturbance:

D1: A sudden disturbance of pressure change at throttle value with -0.2 bar, corresponding to a step change at 100% load.

D2: A sudden disturbance of pressure change at throttle value with -0.2 bar, corresponding to a step change at 50% load.

D3: A sudden disturbance of pressure change at throttle value with -0.2 bar, corresponding to a step change at 0% load.

D4: A disturbance of pressure change represented by $A \cdot \sin(\omega t)$ with amplitude $A = 0.2$ bar and frequency $\omega = 0.04$Hz at the throttle valve which corresponds to low frequency movements of inlet valve representing changes in grid frequency at 100% load.

D5: A disturbance of pressure change represented by $A \cdot \sin(\omega t)$ with amplitude $A = 0.2$ bar and frequency $\omega = 0.04$Hz at the throttle valve which corresponds to low frequency movements of inlet valve representing changes in grid frequency at 50% load.

D6: A disturbance of pressure change represented by $A \cdot \sin(\omega t)$ with amplitude $A = 0.2$ bar and frequency $\omega = 0.04$Hz at the throttle valve which corresponds to low frequency movements of inlet valve representing changes in grid frequency at 0% load.

D7: Load transition: ramping up of load from 50% to 100% operating point.

D8: A pressure disturbance represented by $A \cdot \sin(\omega t)$ with amplitude $A = 0.2$ bar and frequency $\omega = 0.04$Hz at the throttle valve and simultaneously
step change of 18% in calorific value over the designed calorific value of
the fuel (coal) at 100% load.

D9: A pressure disturbance represented by $A^* \sin (\omega t)$ with amplitude
$A= 0.2$ bar and frequency $\omega =0.04$Hz at the throttle valve and simultaneoulsy step change of 18% in calorific value over the designed calorific value of the fuel (coal) at 50% load.

D10: A pressure disturbance represented by $A^* \sin (\omega t)$ with amplitude $A= 0.2$
bar and frequency $\omega= 0.04$Hz at the throttle valve and simultaneously step change of 18% in calorific value over the designed calorific value of the fuel (coal) at 0% load.

D11: A pressure disturbance represented by $A^* \sin (\omega t)$ with amplitude $A= 0.2$
bar and frequency $\omega= 0.04$Hz at the throttle valve and simultaneously step change of 18% in calorific value under the designed calorific value of the fuel (coal) at 100% load.

D12: A pressure disturbance represented by $A^* \sin (\omega t)$ with amplitude $A= 0.2$
bar and frequency $\omega= 0.04$Hz at the throttle valve and simultaneously step change of 18% in calorific value under the designed calorific value of the fuel (coal) at 50% load.

D13: A pressure disturbance represented by $A^* \sin (\omega t)$ with amplitude $A= 0.2$
bar and frequency $\omega= 0.04$Hz at the throttle valve and simultaneously step change of 18% in calorific value under the designed calorific value of the fuel (coal) at 0% load.

D14: A pressure disturbance of step change of -0.2 bar at the throttle valve and simultaneously step change of 18% in calorific value over and above the designed calorific value of the fuel (coal) at 100% load.

D15: A pressure disturbance of step change of -0.2 bar at the throttle valve and simultaneously step change of 18% in calorific value over and above the designed calorific value of the fuel (coal) at 50% load.
D16: A pressure disturbance of step change of -0.2 bar at the throttle valve and simultaneously step change of 18% in calorific value over and above the designed calorific value of the fuel (coal) at 0% load.

D17: A pressure disturbance of step change of -0.2 bar at the throttle valve and simultaneously step change of 18% in calorific value under the designed calorific value of the fuel (coal) at 100% load.

D18: A pressure disturbance of step change of -0.2 bar at the throttle valve and simultaneously step change of 18% in calorific value under the designed calorific value of the fuel (coal) at 50% load.

D19: A pressure disturbance of step change of -0.2 bar at the throttle valve and simultaneously step change of 18% in calorific value under the designed calorific value of the fuel (coal) at 0% load.

Table 2.3 shows the earlier research attempt to solve ALSTOM challenge problems I and II for different types of disturbances. It is seen from the table that the control philosophies proposed so far are not fulfilling some of the requirements of challenges I and II. More specifically, the controllers are not yielding satisfactory performance for multiple disturbance one at throttle side (0.2 Sin (2*pi*0.04*t)) and other at input side i.e., a step variation to a level of ±18% change in calorific value with respect to the designed value.

In the present investigation, PID Filter controller optimised by Genetic Algorithm is chosen for gasifier control. Despite rapid evolution in control hardware, the Proportional–Integral–Derivative (PID) controller remains the workhorse in process industries. The P action (mode) adjusts controller output according to the size of the error. The I action (mode) can eliminate the steady state offset and the future trend is anticipated through the D action (mode). These useful functions are highly useful in large number of process applications.
Table 2.3 Earlier Research attempt to solve Alstom challenge problems I & II

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Authors</th>
<th>Controller methods</th>
<th>Disturbances for which control requirements have been met are indicated by √ while ‘x’ indicates partial fulfilment of control requirements or these disturbance aspects are not covered / available for comparison.</th>
</tr>
</thead>
</table>
| 1     | Liu et al., (2000)         | Baseline PI controller (First Challenge) | D1  D2  D3  D4  D5  D6  D7  D8  D9  D10  D11  D12  D13  D14  D15  D16  D17  D18  D19  
|       |                            |                                    | √  √  √  √  x  x  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x |
| 2     | Rice et al. (2000)         | predictive control                  | D1  D2  D3  D4  D5  D6  D7  D8  D9  D10  D11  D12  D13  D14  D15  D16  D17  D18  D19  
|       |                            |                                    | √  √  √  √  x  x  x  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x |
| 3     | Taylor et al. (2000)       | Proportional integral plus (PIP)    | D1  D2  D3  D4  D5  D6  D7  D8  D9  D10  D11  D12  D13  D14  D15  D16  D17  D18  D19  
|       |                            |                                    | √  √  √  √  x  x  x  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x |
| 4     | Prempain et al. (2000)     | H-infinity control                  | D1  D2  D3  D4  D5  D6  D7  D8  D9  D10  D11  D12  D13  D14  D15  D16  D17  D18  D19  
|       |                            |                                    | √  √  √  √  x  x  x  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x |
|       |                            |                                    | √  √  √  √  x  x  x  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x |
|       |                            |                                    | √  √  √  √  x  x  x  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x |
| 7     | C S Chin and N Munro (2003) | LQG/LTR controller                  | D1  D2  D3  D4  D5  D6  D7  D8  D9  D10  D11  D12  D13  D14  D15  D16  D17  D18  D19  
|       |                            |                                    | √  x  x  √  x  x  x  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x |
|       |                            |                                    | √  √  √  √  √  √  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x |
|       |                            |                                    | √  √  √  √  √  √  √  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x |
| 10    | Rudy Agustriyanto and Zhang (2006) | Generalised relative disturbance gain analysis technique | D1  D2  D3  D4  D5  D6  D7  D8  D9  D10  D11  D12  D13  D14  D15  D16  D17  D18  D19  
|       |                            |                                    | √  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x |
|       |                            |                                    | √  √  √  √  √  √  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x  √  √  √  √  x  x  x  x  x  x  x  x  x  x  x |
Table 2.3 (Continued)

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Authors</th>
<th>Controller methods</th>
<th>Disturbances for which control requirements have been met are indicated by √ while ‘x’ indicates partial fulfilment of control requirements or these disturbance aspects are not covered / available for comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>C J Taylor et al. (2006)</td>
<td>PIP controller</td>
<td>D1  D2  D3  D4  D5  D6  D7  D8  D9  D10  D11  D12  D13  D14  D15  D16  D17  D18  D19</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>√    √    √    √    √    x    x    x    x    x    x    x    x    x    x    x    x    x</td>
</tr>
<tr>
<td>13</td>
<td>Al seyab and Cao (2006)</td>
<td>Non linear predictive controller</td>
<td>√    √    √    √    √    x    x    x    x    x    x    x    x    x    x    x    x    x</td>
</tr>
<tr>
<td>14</td>
<td>Wilson et al., (2006)</td>
<td>state estimators to improve on the base line performance[45]</td>
<td>√    √    √    √    √    x    x    x    x    x    x    x    x    x    x    x    x    x</td>
</tr>
<tr>
<td>15</td>
<td>Amin Nobakhti (2008)</td>
<td>Self adaptive differential evolution</td>
<td>√    x    x    √    x    x    x    x    x    x    x    x    x    x    x    x    x    x</td>
</tr>
<tr>
<td>16</td>
<td>Yong Wang et al., (2009)</td>
<td>Study on Fuzzy Gain-Scheduled Multiple Mode Predictive</td>
<td>√    √    √    √    √    x    x    x    x    x    x    x    x    x    x    x    x    x</td>
</tr>
<tr>
<td>17</td>
<td>Xue et al., (2010)</td>
<td>Multi objective optimisation using NSGA II</td>
<td>√    √    √    √    √    x    x    x    x    x    x    x    x    x    x    x    x    x</td>
</tr>
<tr>
<td>18</td>
<td>W. Tan et al., (2011)</td>
<td>Partially decentralized control</td>
<td>√    √    √    √    √    √    x    x    √    √    √    x    x    x    x    x    x    x</td>
</tr>
<tr>
<td>19</td>
<td>L. Sivakumar and Kooteeswaran (2013)</td>
<td>PI with Fire Fly Algorithm</td>
<td>√    √    √    √    √    x    x    x    x    x    x    x    x    x    x    x    x    x</td>
</tr>
<tr>
<td>20</td>
<td>Kooteeswaran and L. Sivakumar (2013)</td>
<td>Bat algorithm based re-tuning of PI controller</td>
<td>√    √    √    √    √    x    x    x    x    x    x    x    x    x    x    x    x    x</td>
</tr>
<tr>
<td>21</td>
<td>Kooteeswaran and L. Sivakumar (2014)</td>
<td>PI with Cuckoo Algorithm</td>
<td>√    √    √    √    √    x    x    x    x    x    x    x    x    x    x    x    x    x</td>
</tr>
<tr>
<td>22</td>
<td>Kooteeswaran and L. Sivakumar (2014)</td>
<td>MOPSO algorithm</td>
<td>√    √    √    √    √    x    x    x    x    x    x    x    x    x    x    x    x    x</td>
</tr>
</tbody>
</table>
From Pneumatic control through direct digital control to the DCS, PID controllers made greater impact. Using PID control, many sophisticated regulatory control strategies, override control, start-up and shut-down strategies can be designed. This provides the basic means for good regulatory, smooth transient, safe operation and fast start-up and shut-down. Moreover, PID controllers serve as the fundamental building block at the regulatory level even with model predictive control (MPC). The computing power of microprocessors provides additional features, such as automatic tuning, gain scheduling and model switching, to the PID controller (Cheng-Ching, 2007).

Nearly 97% of industrial applications uses PID algorithms. For the rare cases of complex dynamics or significant dead time, other algorithms are used. On many occasions, engineers finds difficult in tuning and takes long period of time. It then becomes obvious that the PID controller with an automatic tuning feature is an attractive alternative for better control after the publication of Zeigler-Nicholas tuning method (O’Dwyer, 2009). In this thesis, PID controller is used to achieve the desired performance of the gasifier by choosing the appropriate values for the controller constants. Usually, due to numerical constraints, these types of problems are being solved by soft computing approaches. Heuristic approaches are well suited for this kind of situations. With this approach it is easier to get local optima and using these local optima as initial seeds successively it is possible to move towards Global optimization. These optimization algorithms requires less time as compared to analytical procedures features (Cheng-Ching, 2007).

Genetic Algorithms (GA) (Herrero et al 2002) are optimization techniques that uses the laws of natural selection onto the population to achieve individuals that could be better adjustable to their environment. The set of points in the search space are called population. Each individual of the population represents a point in that space by means of chromosome. The individual’s degree of adaptation is given by the objective function. Applying genetic
operators to an initial population simulates the evolution mechanism of individuals. The most usual operators are as follows:

(i) Selection: The main goal is selecting the chromosomes with the best qualities for integration in the next generation (these would depend on the cost function for each individual).
(ii) Crossover: New chromosomes are generated by combining two chromosomes and it is further integrated into the population.
(iii) Mutation: New individuals are generated by random variations of parts of the chromosome of an individual in the population.

GA have demonstrated very good performances as global optimisers in many types of applications (Blasco, 1999).

**2.10 CONCLUSION ON LITERATURE REVIEW:**

IGCC technology for power generation is likely to take off due the following reasons

i. Environmental friendliness
ii. Higher efficiency of operation compared to pulverized coal technology
iii. Lesser cost/kwh of electrical generation considering the cost of carbon dioxide capture and sequestration.

A detailed mathematical model of IGCC will be of useful to plan the different operational strategies and design suitable control strategies for safe and efficient operation. However, plants with combined cycle operation have been in existence quite long and their operational strategies, control philosophies and dynamic transient performances are well understood with mathematical models and dynamic field tests. At this juncture, what is needed is a mathematical model for gasifier to do transient performance analysis and design suitable controllers.
This has become possible in the wake of ALSTOM providing mathematical model for the Gasifier and posing the academic community to come out with suitable control strategies for special type of disturbances.

Broadly, two approaches have been found in the literature to evaluate the gasifier performance:

(i) Consider the higher order state space model as given by Alstom and try to tune the base line PI control using optimization algorithms such as Non dominated sorting genetic algorithm (NSGA) II (Xue et al. 2010), Multi objective genetic algorithm (Simm and Liu 2006), PI optimization using cuckoo search algorithm, Normalized Normal Constraint algorithm, Bat algorithm, Firefly algorithm (Kotteeswaran and Sivakumar 2013) and Particle Swarm Algorithm (Kotteeswaran and Sivakumar 2014).

(ii) Consider the higher order state space model as given by Alstom but try modern control algorithms such as model predictive control (Seyab 2006), H∞ control (Prempain et al. 2000), Sequential loop closing approach (Munro et al. 2000), state estimation approach (Wilson et al. 2006), multi variable proportional integral plus control (Liu et al. 2000), partially decentralized control (Tan et al. 2011), self-adaptive differential evolution algorithm (Amin, 2008), active disturbance rejection control (Huang et al. 2013), etc. for performance evaluation.

All the attempts of different investigators led to reasonable success in terms controlling the gasifier. However, the overall performance requirements stated in the challenges I and II have not been met fully and thus lending an opportunity to work on these challenge problems.