CHAPTER 3

CONTROL STUDIES OF COMPONENTS

Many advanced controllers are available for controlling the systems in process control stations. But predominantly PID controllers are widely used in many of these industries. Hence proper tuning of PID controller is required to keep the output in a controlled manner. Detailed control tuning algorithms are discussed in this chapter and the application of these control algorithms pertaining to the various sub-systems of Circulating Fluidized Bed Combustion Boilers is presented in the next chapter and the simulation results are given.

3.1 CONTROL PHILOSOPHY AND PARAMETERS FOR THE DESIGN AND EVALUATION OF CONTROLLER

Process knowledge is essential for automatic control of a process. Control of CFB boiler involves the pressure, temperature and level control. The critical process parameters for the control of CFB boiler are well described. The inputs, the outputs and the controlled variables are listed below in table 3.1 for better understanding.
Table 3.1  Input, Output and controlled variables of CFBC boiler sub-systems

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
<th>Controlled variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal flow</td>
<td>Main steam ash</td>
<td>Main steam pressure</td>
</tr>
<tr>
<td>Primary air flow</td>
<td>hot reheat steam</td>
<td>Main steam temperature</td>
</tr>
<tr>
<td>Secondary air flow</td>
<td>flue gas</td>
<td>Drum level</td>
</tr>
<tr>
<td>Feed water flow</td>
<td>Ash</td>
<td>Drum pressure</td>
</tr>
<tr>
<td>Spray flow</td>
<td></td>
<td>Furnace temperature</td>
</tr>
<tr>
<td>Solid particles flow</td>
<td></td>
<td>Furnace pressure</td>
</tr>
<tr>
<td>Cold reheat steam</td>
<td></td>
<td>Re-heater steam temperature</td>
</tr>
</tbody>
</table>

In order to control the variables, the following six controllers are used. They are

- P controller
- PI controller
- PD controller
- PID controller

Three mode controllers with proportional, integral and derivative (PID) elements gained importance during 1930s. A Proportional controller provides a proportional action to the input signal, integral term eliminates the steady state error and the derivative term reduces the oscillations. Therefore, the controller with proper gain yields good results with linear and nonlinear systems considering small parameter variation.

Though many advanced controllers like Fuzzy controller, neuro controller, Hybrid controller, model predictive controllers are available, still
PID control gains importance in the process control applications and is given by the following equation

$$c(t) = K_p e(t) + K_i \int_0^t e(t) \, dt + K_d \frac{de(t)}{dt} \quad (3.1)$$

where $c(t)$ is the control variable, $e(t)$ is the error signal and $K_p$, $K_i$, and $K_d$ the proportional, integral and derivative gain.

Control Engineers have the responsibility of obtaining the proper $K_p$, $K_i$, $K_d$ parameters. The two main categories of tuning the PID controller are open loop methods and closed loop methods. The open loop methods are generally tuned manually and the closed methods tuned automatically. The classical control algorithm used for tuning under open loop methods are

1. Ziegler Nichols open loop step response (ZN) method
2. Chen-Hrones and Reswick (CHR) method
3. Cohen –Coon Method
4. Internal Model controller (IMC) method
5. Fertik Method
6. Minimum Error Criteria method

The closed loop methods used for tuning are

1. Ziegler Nichols method
2. Modified Ziegler Nichols method
3. Tyreus – Luyben method
4. Damped oscillation method
Some of the open loop and closed loop tuning methods which are discussed in this chapter are used in the next chapter for obtaining the performance of the system.

3.2 OPEN LOOP TUNING ALGORITHMS OF PID CONTROLLER

3.2.1 Ziegler Nichols open loop step response (ZN) method

In this chapter, the analysis of some PID tuning algorithms that are based on the first order model is presented here when a step input is applied. Firstly, the proportional value defined should be within the admissible limit. Then the integral and derivative gain values are examined so that the tuning rules exhibit robustness with respect to the controller parameter change.

(Source: L. Sivakumar et al., 2016)

Figure 3.1 Determination of open loop parameters from unit step response using Ziegler Nichol’s response method
Applying the step input, the parameters ‘a’ and ‘L’ are determined from the open loop response as shown in Figure (3.1). For PID parameters, the point where the slope of the maximum response is determined and a tangent is drawn at that point. The intersection of that tangent with the ‘X’ and ‘Y’ axis gives the ‘L’ and ‘a’ values. This is obtained from the following table (3.2).

### Table 3.2 Controller parameters of P, PI, PID controllers using ZN open loop response method

<table>
<thead>
<tr>
<th>Parameter</th>
<th>P</th>
<th>PI</th>
<th>PID</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_p$</td>
<td>$\frac{1}{a}$</td>
<td>$\frac{0.9}{a}$</td>
<td>$\frac{1.2}{a}$</td>
</tr>
<tr>
<td>$T_i$</td>
<td>-</td>
<td>3L</td>
<td>2L</td>
</tr>
<tr>
<td>$T_d$</td>
<td>-</td>
<td>-</td>
<td>$\frac{L}{2}$</td>
</tr>
</tbody>
</table>

The optimum controller configuration has been proposed with the two process parameters and they are normalized dead time ($\tau$) and gain ratio ($k$) where normalized dead time is given by $\tau = \frac{L}{L+T}$ where ‘T’ is the time constant of the system. Similarly, the gain ratio ($k$) is given by ratio of process gain at the frequency has sustained oscillations to the steady state gain.

#### 3.2.2 Chein-Hrones and Reswick (CHR) method

This method has been suggested for two conditions

(i) Response without overshoot

(ii) Response with 20% overshoot
The tuning of controller is made for both the set-point change and disturbance change. They are tuned only for 100% load and is given by the following table 3.3

Table 3.3  **Controller parameters of P, PI, PID controllers using CHR method with and without overshoot**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>0% overshoot in SP</th>
<th>20% overshoot in SP</th>
<th>0% overshoot For disturbance</th>
<th>20% overshoot For disturbance</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>P</td>
<td>PI</td>
<td>PID</td>
<td>P</td>
</tr>
<tr>
<td>K&lt;sub&gt;p&lt;/sub&gt;</td>
<td>0.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.35&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.6&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.7&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>T&lt;sub&gt;i&lt;/sub&gt;</td>
<td>-</td>
<td>1.2T</td>
<td>T</td>
<td>-</td>
</tr>
<tr>
<td>T&lt;sub&gt;d&lt;/sub&gt;</td>
<td>-</td>
<td>-</td>
<td>L/2</td>
<td>-</td>
</tr>
</tbody>
</table>

Tuning of Cascade controller like P-PID and PI-PID is based on the CHR method. Tuning of Master controller (MC) and the Slave controller (SC) is again done for 100% load and the results are obtained.

3.2.3  **Cohen –Coon Method**

Ziegler Nichol’s method works well when the dead time is half the length of the time constant. But Cohen – coon method works well even if the dead time is less than two times the time constant. Interactive, non-interactive and parallel are the three types of PID controller algorithms. Cohen –Coon methods comes under the non-interactive type of PID control algorithm.
It is applicable to process where the response is faster. Process gain, dead time and time constant are the three process parameters or characteristics which are involved in the Cohen-Coon tuning algorithm. Tuning of Cohen-Coon algorithm involves the following process:

1. The controller is to be placed in manually.
2. When the process settles out, a change is made in the controller output (CO).
3. Wait for the process variable (PV) to settle down to a new value. Process gain (Gp) is calculated as follow:
   \[ G_p = \frac{\text{Change in PV (in %)}}{\text{Change in CO (in %)}} \]
4. The inflection point is identified and a tangential line is drawn.
5. Dead time (td) is measured. It is the time difference between the change in CO and the intersection of the tangential line and the original PV level.
6. Time constant \( \tau \) is measured

![Figure 3.2 Response curve of Cohen – Coon method](image-url)
The tuning rules for Cohen-Coon method is given below in Table 3.4 for PI and PID controllers and the response curve in Figure 3.2.

**Table 3.4  Controller parameters of PI, PID controllers using Cohen coon method**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PI</th>
<th>PID</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_p$</td>
<td>$\frac{0.9}{\tau_p} \left[ \frac{\tau}{t_d} + 0.092 \right]$</td>
<td>$\frac{1.35}{\tau_p} \left[ \frac{\tau}{t_d} + 0.185 \right]$</td>
</tr>
<tr>
<td>$T_i$</td>
<td>$3.33t_d \left[ \frac{\tau + 0.092t_d}{\tau + 2.22t_d} \right]$</td>
<td>$2.5t_d \left[ \frac{\tau + 0.185t_d}{\tau + 0.611t_d} \right]$</td>
</tr>
<tr>
<td>$T_d$</td>
<td>-</td>
<td>$0.37t_d \left[ \frac{\tau}{\tau + 0.185t_d} \right]$</td>
</tr>
</tbody>
</table>

**3.2.4 Internal Model Control**

This method is open loop stable. This method is mainly used in process control applications where the control algorithm is an inverse of the process model for which the output needs to be controlled. IMC control poses internal stability problem and hence IMC based PID controller is used. IMC based PID control offers good set point tracking. The structure of the IMC architecture is shown in Figure 3.3 and the controller parameters in Table 3.5.

![Figure 3.3  Basic structure of IMC controller](image-url)
Consider the system transfer function to be \( G_m \) for a Super-heater

\[
G_m = k \frac{e^{-Ls}}{1 + sT}
\]

The transfer function of IMC controller is given by

\[
G_c = \frac{G_i}{1 - G_i G_m}
\]

Table 3.5  Controller parameters of PI, PID controllers using IMC model

<table>
<thead>
<tr>
<th>Controller configuration</th>
<th>Kp</th>
<th>Ti</th>
<th>Td</th>
<th>T1</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>( \frac{T}{k\lambda} )</td>
<td>T</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>( \frac{(2T + L)}{2k(\lambda + L)} )</td>
<td>( T + \frac{L}{2} )</td>
<td>( \frac{TL}{2T + L} )</td>
<td>( \frac{\lambda L}{2(\lambda + L)} )</td>
</tr>
</tbody>
</table>

Here \( \lambda > 0.25L \) and \( \lambda > 0.25L \) for a PID controller and for a PI controller \( \lambda > 1.7L \) where \( \lambda \) is the uncertainty factor.

3.2.5  Modified Ziegler–Nichols Tuning

Modified Ziegler–Nichols tuning methods are closed loop methods applicable to PI and PID controllers and the estimation of the controller parameters using modified Ziegler Nichol’s tuning is given in the table 3.6.
Table 3.6  Estimation of PI, PID Controller parameters using Modified Ziegler Nichol’s tuning

<table>
<thead>
<tr>
<th>Controller configuration</th>
<th>Kp</th>
<th>Ti</th>
<th>Td</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>0.33KP</td>
<td>0.5PU</td>
<td>0.333 P_U</td>
</tr>
<tr>
<td>PID</td>
<td>0.2 KP</td>
<td>0.5PU</td>
<td>0.333 P_U</td>
</tr>
</tbody>
</table>

3.2.6  Tyreus – Luyben tuning

This method is applicable only to PI and PID controllers. The Kp gain is increased until it reaches the ultimate gain Ku where the Ki and Kd are set to zero. When Kp reaches Ku, the output of the loop will tend to oscillate. The tuning parameters Ku and Tu for PI and PID controller are given below in the table 3.7

Table 3.7  Estimation of PI, PID Controller parameters using Tyreus – Luyben tuning

<table>
<thead>
<tr>
<th>Controller configuration</th>
<th>Kp</th>
<th>Ki</th>
<th>Kd</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>0.3125Ku</td>
<td>Kp/2.2TU</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>0.4545Ku</td>
<td>Kp/2.2TU</td>
<td>KpP_U/6.3</td>
</tr>
</tbody>
</table>

3.3  MAIN CONTROL LOOPS IN A CFBC BOILER

The different control loops of CFBC boiler are given below and elaborated in chapter four.
3.3.1 Drum level and pressure control

The basic block diagram and level controller circuit of a circulation system is shown in Figure 3.4 and Figure 3.5. The level control circuit consists of disturbance variables like actual level of the drum, feed water flow, spray flow and main steam flow for the given system. The change in the main steam flow results due to the change in the demand. In order to control the level of the drum, the set point is compared with that of the actual level of the drum as described by Thenmozhi.G et al. (2016)

![Block Diagram of CFBC Boiler](image)

**Figure 3.4** Alternate representation of circulation system of CFBC boiler
Due to the sluggish output, a cascade (PI-PID) control is used. The control algorithm consists of two controllers namely the Master Controller (MC) and Slave Controller (SC). PID controller is configured as a master controller and PI controller acts as a slave controller. The master controller has a set-point value comparable with the actual drum level and is compared with that of the main steam flow and economizer flow.

The parameters that are considered for our analysis are

1. Peak overshoot
2. Rise time
3. Settling time
4. Integral of absolute error (IAE)
5. Integral of time weighted absolute error

(Source : Thenmozhi, 2016)

Figure 3.5  Level controller for circulation system of CFBC boiler
Among these parameters the peak overshoot and IAE are considered for step change in disturbance and all the parameters are considered for the step change in set-point. The control system is designed usually for better stability and is normally measured from step response. The main parameter is said to be the peak overshoot for the system. The acceptable overshoot of the system is around 30%. These parameters affect the system gain and phase margin. Further changes in the disturbance would cause change in the gain and phase margin. For robust design, the control system is designed for a variation of 10% in all the process parameters.

Drum pressure is normally affected by the load changes. When the load increases, the steam drawn is more and hence the pressure in the drum drops. Similarly when the load is reduced, the steam drawn is less and hence the pressure in the drum of the circulation system is increased. Due to this pressure build up, the safety measures come into play. Hence, the pressure control plays a crucial role in the drum.

3.3.2 Main Steam Temperature Control

Main steam flow, drum pressure and heat input are the three variables that play a major role in the Super-heater temperature control. The main components discussed in the main steam temperature control loop are super heater, attemperator, control valve and temperature sensor. The Superheating system under 210MW boiler consists of Low Temperature Super Heater (LTSH), Super-heater I (SH-I), Super-heater II (SH-II) and Final Super-heater (FSH).
In this chapter, an analysis of first order model is presented and various tuning techniques are analyzed. Certain parameters are considered for the evaluation of the controllers subjected to a single or series of disturbances. The heat input and inlet steam temperature are to be applied together. Figure 3.6 shown above consists of a single PID controller. When a cascade control is made use of, the Master Controller (MC) is configured to be a PID controller and the slave controller to be PI controller. The output of the MC actuates the SC. The controllers are tuned for a step change of 1°C in the set-point. While tuning the cascade controller as shown in Figure 3.7, care should be taken such that the slave controller is tuned first and then the master controller is tuned.
3.3.3 Main Steam Pressure Control

The critical parameters that are to be controlled in the turbine side are the main steam temperature and pressure. The main steam pressure control is also called the Master Pressure Control. Variation in the main steam pressure due to the change in calorific value of the fuel has been well described by Dharmalingam et al. (2011). When the load is increased, the main steam pressure also varies accordingly. The difference between the set point and the main steam pressure is given as the boiler demand which in turn controls the fuel flow and air flow and this is represented in Figure 3.8.
3.3.4 Bed Temperature Control

Proper and complete combustion of fuel is the major factor which enhances the efficiency. The bed (furnace) temperature control is the key factor which influences combustion control. Complete combustion takes place when proper air and fuel mixture is supplied at higher temperature. To ensure complete combustion, an additional amount of air called the excess air is supplied to the chamber. Some of the O₂ molecules escape through the flue gases. The basic equation for the excess air calculation and O₂ concentration percentage is studied in Liptak (1999). The recommended excess air level for coal is 20 to 25%.
With adequate air, when the fuel flow is increased, the bed temperature increases which leads to big disaster unless it is controlled and hence, the bed temperature control plays an important role in the CFBC boilers and at this temperature the emissions are comparatively less Jalali et al.(2007) The temperature of the bed is maintained at 850° - 880° C. The fluidization velocity is maintained between 4-6m/s. In the case of CFBC boiler, in addition to primary air, secondary air, flue gases and fuel, solid particles also contribute to the inlet energy of the furnace since the solid particles are re-circulated to the furnace through the two cyclone separators.

3.3.5 Re-heater Temperature Control

The Re-heater steam temperature and the super heater steam temperature are to be maintained at optimum level so that the efficiency of the system is high and also the lifetime of the water tubes are increased. Heat input from the furnace back pass, cold reheate temperature, inlet steam temperature and spray flow are the variables that affect the outlet temperature of the Re-heater and the control of steam temperature in the Re-heater is shown in Figure. 3.9. For a step change of 1°C temperature in the set-point, parameters like rise time, peak overshoot, settling time, integral of absolute error (IAE), integral time of absolute error (ITAE) are evaluated. A step change of 1% for heat input and 1°C for steam inlet temperature are applied together concurrently. For a disturbance in set point, maximum peak overshoot and IAE is evaluated. This is applicable for both Super-heater and re-heater.
3.3.6 Furnace Pressure Control

The main objective of this control system is to keep the furnace pressure slightly below the atmospheric pressure so that the process of combustion of the system is stable. Change in the fuel causes change in the inlet gas flow. Correspondingly there is a change in the pressure ($\Delta P$) inside the furnace. This change or deviation in the pressure when subjected to a change in the fuel has to be controlled within the operating limits which may lead to explosion when it is not controlled properly. If the bed pressure (Furnace pressure) is too high as said by M. Li, X. D. Xu (2002), the particles under fluidization may be affected and hence they will settle down at the bottom which may lead to poor combustion and less efficiency.
Figure 3.10 is the block diagram which explains the operation of the furnace pressure control. The set point value is compared with that of the actual furnace pressure and the error signal is fed back to the PID controller which in turn controls the speed control and vane position of the Induced draught (ID) fan. If the pressure in the furnace is increased, more vane opening is increased and more gas is let out.

3.4 SUMMARY

The controllers and its tuning methods have been described elaborately in this chapter. Though a wide variety of tuning methods are available, the classical methods of tuning are Ziegler Nichols method, Cohen Coon method and CHR method. The control loops of CFBC boilers are listed and their performance is well described in the next chapter.