CHAPTER 6

DESIGN OF INTEGRATED BOILER AND CONTROL SYSTEM MODEL

6.1 INTRODUCTION

The steam generation plants are designed for particular output conditions so that the best possible efficiency is achieved. The output steam pressure and temperature are controlled to predetermined values within limited variations. The quantity of steam to be produced is varied as per the demand. The turbo-generator operates based on the steam generator output. A set of operating procedures are laid down to achieve the desired efficiency and these procedures are concerned with the various equipments of the power plants. All the equipments have to operate as an integrated system to achieve the desired output with best efficiency and safety. The numerous process variables and conditions to be co-ordinated in the power plant calls for an effective automatic control system (Lausterer and Kandel 1983, Patel 1988, Vahldieck and Krause 1988, Sam 1991, Nomura and Ogura 1985, Research report of EPRI 1983, Marganovic 1985, Gorden Pellegrinette et al 1991, Michael 1991, Uchida et al 1986, Whalley 2000, Raul 2000 and Tilman Tutken 1996).

It is important that the automatic control system is designed and tuned to form an integral part of the power plant, like the nervous system of a human body, because during the running condition of the plant, each and every part of
the plant is to be monitored and controlled so as to achieve the desired operation of the plant. PID controllers are quite common even today in almost all the plants and experienced plant operators know how to tune them for the plants in hand (Cecil L. Smith 1972, Pradeep B. Deshpande and Ash 1981, Chidambaram 1988 and John Azzo 1988). Similarly, if we simulate the regulated operation of the plant, control system models are to be incorporated into the integrated model of the boiler.

This chapter describes the design and simulation of an Integrated boiler and control system model that could be used as a boiler simulator for operator training. The Integrated boiler model is combined with the following important control systems of the boiler as shown in Figure 6.1 to realize stabilized operation of the plant.

a. Master pressure control system
b. Drum level control system
c. Main steam temperature control system

Algorithms based on PID controllers are used to implement the above control systems.

6.2 MASTER PRESSURE CONTROL SYSTEM

Following control algorithm is used for the Master pressure controller:

Let \[ e_p(k) = p_a(k) - s_p \] (6.1)
Figure 6.1 Integrated Boiler model augmented with Conventional Control System
where $e_p(k)$ denotes the error between the measured steam pressure $p_s(k)$ and the steam pressure set point $s_p$ at time instant $k$.

The fuel flow is controlled by the PID algorithm,

$$F_f(k) = F_f(k-1) + k_{pp} [e_p(k) - e_p(k-1)] - \frac{k_{pp}}{\tau_{ip}} \tau e_p(k)$$

$$\frac{k_{ip}}{\tau} \tau_{dp} [e_p(k) - 2e_p(k-1) + e_p(k-2)]$$  \hspace{1cm} (6.2)

where
- $k_{pp}$ - Proportional gain
- $\tau_{ip}$ - Integral time
- $\tau_{dp}$ - Derivative time
- $\tau$ - Sampling period

The air flow control signal is derived by multiplying the fuel flow control signal by the stoichiometric air/fuel ratio $\varepsilon$. The controller is tuned by adjusting $k_{pp}$, $\tau_{ip}$ and $\tau_{dp}$ until the $1/4$ ratio decay performance criterion is achieved. That is if $e_1$ and $e_2$ denote the first and second overshoots of the controlled response, then the controller tuning should be such that

$$\frac{e_2}{e_1} < \frac{1}{4}$$

During real time implementation, we must ensure 'air excess' situation in the furnace at all times, in order to ensure furnace safety and complete combustion. For this purpose, the selective system shown in Figure 6.1 is to be used together with the pressure control system in real time implementations.
The flow of feed water $F_{ew}$ to the boiler drum is normally controlled in order to hold the level of the water $l_2$ in the steam drum as close as possible to the normal water level setpoint $s_1$. A typical level control loop would measure level with a level sensor, process this measurement in a PID controller and control $F_{ew}$ with the feed water control valve. This typical level control system known as 'single element control system' is inadequate for boiler drum level control. The inadequacy results from the 'shrink' and 'swell' characteristics of the boiler, which produce level changes in a direction opposite to which level would be expected to change with the particular load change. For this reason, control from level alone will produce an incorrect control action any time the boiler load changes (Sam Dukelow 1991). In order to take care of the above inadequacy in the drum level control system, a 'Three -element control system' is considered. The three element control system considers three variables viz. $F_{ew}$, $l_4$ and $F_s$. Two PID controllers are used, one is known as Level controller and the other as Three element feed water controller. The level controller generates a control signal based on the variation in the drum level. This control signal is multiplied with a gain $\Psi_d$ and then added with the main steam flow. The resulting signal acts as setpoint to the Three element feed water controller. The Three element controller compares the feed water flow with the derived setpoint and regulates the feed water flow by the feedwater control valve, till the drum level reaches the setpoint.

Following algorithm is used for realizing the three element feedwater control system:
Level Controller

Let $e_i(k)$ represent the error signal for the drum level controller, i.e., $e_i(k) = l_d(k) - s_i$ \hspace{5cm} (6.3)

The level controller output $q_0$ is given by the PID algorithm,

\[ q_0(k) = q_0(k-1) + k_{pi} \left[ e_i(k) - e_i(k-1) \right] \frac{k_{pi} \tau_{il}}{\tau} e_i(k) \]

\[ + \frac{k_{pi} \tau_{il}}{\tau} \left[ e_i(k) - 2e_i(k-1) + e_i(k-2) \right] \]

where \hspace{5cm} (6.4)

- $k_{pi}$ - Proportional gain
- $\tau_{il}$ - Integral time
- $\tau_{di}$ - Derivative time.

Three element controller

The error signal $e_w$ for the Three element controller is defined as

\[ e_w(k) = F_{ew}(k) - \Psi_d q_0(k) - F_s \] \hspace{5cm} (6.5)

The three element controller generates its output $F_{ew}(k)$ by the algorithm,

\[ F_{ew}(k) = F_{ew}(k-1) + k_{pw} \left[ e_w(k) - e_w(k-1) \right] \]

\[ + \frac{k_{pw} \tau_{iw}}{\tau} e_w(k) \]

\[ + \frac{k_{pw} \tau_{dw}}{\tau} \left[ e_w(k) - 2e_w(k-1) + e_w(k-2) \right] \] \hspace{5cm} (6.6)

where \hspace{5cm} (6.6)

- $k_{pw}$ - Proportional gain
- $\tau_{iw}$ - Integral time
- $\tau_{dw}$ - Derivative time.
The dynamics of the feedwater control valve is neglected in the controller implementation. The controller settings $k_{pl}$, $\tau_{dl}$, $k_{pw}$, $\tau_{tw}$, $\tau_{dw}$ and the gain factor $K_d$ are tuned so as to obtain a decay ratio of $\frac{1}{4}$ in the controlled response of drum level.

### 6.4 MAIN STEAM TEMPERATURE CONTROL SYSTEM

The main purpose of the main steam temperature control system is to obtain as nearly as possible a constant superheated steam temperature at all boiler loads. Attemperator spray is used to control the steam temperature immediately, using a PID controller. The steam temperature controller uses the following algorithm:

Let $e_s(k) = T_s(k) - s_s$ \hspace{1cm} (6.7)

represent the error signal. The main steam temperature controller output is described by the equation:

$$F_{spa}(k) = F_{spa}(k-1) + k_{ps} \left[ e_s(k) - e_s(k-1) \right] + \frac{k_{ps}}{\tau_{is}} \tau e_s(k)$$

$$+ \frac{k_{ps} \tau_{ds}}{\tau} \left[ e_s(k) - 2e_s(k-1) + e_s(k-2) \right]$$

(6.8)

where $k_{ps}$ - Proportional gain

$\tau_{is}$ - Integral time

$\tau_{ds}$ - Derivative time

The controller settings $k_{ps}$, $\tau_{is}$, and $\tau_{ds}$ are tuned such that a decay ratio of $\frac{1}{4}$ is obtained in the controlled response of SSH.
The integrated boiler model has been augmented with the control system models of Master pressure, Drum level and Main steam temperature as shown in Figure 6.1. Simulation studies are conducted in order to study the controlled performance of the boiler. Figure 6.2 presents the response of the boiler furnace for a 5% increase in fuel flow when the steam temperature, steam pressure and drum level are controlled. It depicts the controlled dynamics of the furnace in terms of furnace heat transfer, furnace gas temperature, furnace gas pressure and exhaust gas energy. All variables in the furnace attain steady state in 150 to 175 seconds time.

Figure 6.3 gives the response of the boiler drum under the same fuel flow condition. It is observed that the drum responses also reach steady state in 150 to 175 secs. Figures 6.4 and 6.5 show the controlled responses of the boiler when the plant is initially subjected to 5% increase in the fuel flow and a +5% load variation (main steam flow) is applied from the 350th instant onwards. Figure 6.6 presents the controlled response of main steam temperature when a 5% increase in fuel flow is applied. The main steam temperature takes about 360 secs to reach steady state. This is further worsened when a +5% load variation is applied from the 350th instant onwards as is clear from Figure 6.7. With this step load variation, the boiler appears to take about 535 secs to attain steady state. If the load is a continuously varying one which is often the case in a power plant, achieving accurate control of main steam temperature will be a very difficult task. The simulation studies give a clear picture that the steam temperature is the most difficult variable to control in a power plant boiler.
Figure 6.2 Response of Boiler Furnace when drum Level, steam pressure and steam temperature are controlled (5% increase in fuel flow applied)
Controller Settings

Pressure Control

\[ \frac{\Delta P}{\Delta T} = 10 \text{ kg/sq.cm} \]
\[ T_p = 64 \text{ Sec} \]

Drum Level Control

\[ L_d = 88.90 \text{ cm} \]
\[ T_d = 7.0 \text{ Sec} \]
\[ T_d = 17.0 \text{ Sec} \]
\[ T_d = 1.0 \text{ Sec} \]
\[ T_d = 2.8 \text{ Sec} \]
\[ T_d = 8.0 \text{ Sec} \]

Drum Water Volume (cm³)

\[ \frac{\Delta V}{\Delta T} = 0.2 \text{ Sec} \]

Figure 6.3 Controlled response of Integrated Boiler Model (5% increase in fuel flow applied)
Figure 6.4 Response of Boiler Furnace when all variables are controlled
(+5% load variation is applied from 350th sampling instant onwards)
**5% increase in Fuel Flow applied initially**

**+5% load variation applied from 350th instant onwards**

Figure 6.5 Controlled Response of Integrated Boiler Model
Figure 6.6 Controlled Response of Main Steam Temperature for 5% increase in fuel flow

Controller Settings

- $T_S = 540 \, ^\circ\text{C}$
- $W_1 = 0.1$
- $T_{d1} = 0.8 \, \text{Sec}$
- $T_{d2} = 8.26 \, \text{Sec}$
- $T = 15\, \text{Sec}$
Figure 6.7 Controlled Response of Main Steam Temperature for 5% increase in fuel flow

+6% Load Variation is applied from the 359th instant onwards
6.6 NEED FOR ADVANCED CONTROL

It is quite evident from the foregoing study that, of all the variables in the boiler, the main steam temperature is very difficult to control accurately due to the large process lag associated with the SSH. Hence conventional control systems based on PID controllers would not be able to cater to the needs of the steam temperature control system, if our aim is to improve the boiler efficiency. In the following Chapter, three advanced control systems are proposed for accurately controlling the main steam temperature and to achieve optimum performance. The best controller out of these three control systems is selected for the optimization of main steam temperature.