CHAPTER 4

LOWER ORDER MODELING OF CIRCULATION SYSTEM

4.1 INTRODUCTION

Mathematical Modelling of any system is important to describe its dynamic behavior. It is a challenging task to accurately model complex real time systems like utility boilers which involve a lot of subsystems. A mathematical model basically establishes the relationship between the input and output of a system. The relationship may be

- Linear or Non-linear Algebraic Equations
- Linear or Non-linear Differential/Partial Differential/Time Varying Equations
- Transfer functions
- State Space Models

Generally, there are two modeling approaches that are adopted in order to determine the dynamic model of a system:

- First Principle or Physical model Approach
- Black Box model Approach

In the physical model approach, the system/process is assumed to be well understood. The modeling philosophy is based on the laws of conservation.
of mass, energy and momentum as is applicable to the physical process under consideration. This approach usually results in non-linear model equations consisting of differential and algebraic terms. The coefficients that are derived from the model equations have a wide range of validity and are related to the physical process to a great extent.

In the Black Box model approach, the process may not be completely known or may be too complicated to be modeled by physical laws. Hence, the system under study is modeled using its input output relationship. Experiments are performed and field measurements are obtained for input-output responses, from which the process dynamics are determined. This approach is useful for the overall study of various systems.

Many attempts have been made by researchers to derive the lower order model of a thermal power plant. In the case of field measurements, it is found that performing experiments are expensive, time consuming and are prone to error due to measurement noise and the delays introduced due to the sensing devices. Physical model, on the other hand is more reliable and justified since it is derived from fundamental physical laws. Therefore, when such a detailed physical model is available, it is relatively easy to derive the lower order model of the various subsystems or the overall plant. The input-output data can be precisely obtained for a given region of interest from which the lower order models can be derived to fit these input-output relations using appropriate system identification techniques. The model thus obtained can be tested for a step or any other disturbance and the response analyzed without having to bother about the complexity involved in the system.
In contrast with the methods available in literature, attempts to derive the simplified model of the complex Multiple Input Multiple Output (MIMO) circulation system using the input output data generated from the validated model of a 500 MW thermal power plant at BHEL, Hyderabad is made. This has been done on the basis of literature survey on modeling, plant data knowledge and system identification methodology. The detailed description of the system identification method is discussed and the results are presented.

The usefulness of lower order modeling of a boiler is discussed in this chapter. Based on the input - output data generated from the 500 MW thermal power plant, lower order model of the circulation system, which is one of the most significant subsystem of a utility boiler is obtained and presented.

4.2 LOWER ORDER MODELING

Reduced order or lower order modeling of various subsystems in a power plant is necessary and useful in a number of situations, because it leads to reduced memory requirements for computation. A low-order model of a power plant has a number of uses:

- It can be used for various system analysis studies and to study the effect of controller settings on a system without having to study the detailed mathematical model.
- It also helps one to realize a hardware simulator using analog, digital or hybrid hardware.
- It can be used for the study of power plant malfunction or upset conditions within the limits of the model.
• It can be used for long term stability analysis of the power plant and various diagnostic studies.

In summary, it may be inferred that low-order models for the power plant or its subsystems may be derived using input-output responses obtained from field measurements or from the detailed physical model of the power plant, by employing appropriate system identification techniques in each case. Performing experiments are expensive and time consuming and may involve risk to the physical system; hence they are not easy to conduct. Appropriate input signals, such as a step disturbance in only one input, are not easy to introduce. Moreover, in real time situations, all inputs may vary simultaneously even though disturbance was initially introduced only in one of the input variables. Thus in a multi-input, multi-output system, the output recorded would be the result of simultaneous disturbances in several inputs. This makes the identification job more difficult. Also, the field measurements may be corrupted by noise and also be affected by the response lags in transducers and measuring instruments. These factors also have to be taken care of in the identification algorithms. All of these make the generation of input-output data and the subsequent identification process difficult.

When a detailed mathematical model of a plant, based on its physical knowledge, is available, low-order models of the plant or its subsystems can be obtained. Since the detailed model has been derived from fundamental physical laws and physical data, a basic level of confidence in the validity of the model is justified. Also, by comparing the model’s transients with known trends and field test data, the level of confidence in the model can be further improved.
Several such reasonably well-validated detailed mathematical models of thermal power plants are presently available.

The detailed models of the various power plant subsystems as well as the integrated power plant model have been developed and documented in the company reports of BHEL, Hyderabad. These models are basically non-linear and are valid over a wide range of plant operation. From these detailed models input-output data records can be generated for any of the subsystems or total system, for any kind of disturbance or input. Since these data records are generated on computer from mathematical models, they have the advantage of being devoid of any measurement lag and noise.

With such a detailed mathematical model at one’s disposal, it is relatively easy to obtain low-order models for any portion of the plant, subsystems or overall plant. For the zone of interest, with inputs and outputs identified, specific input signals can be applied and the output can be accurately generated from the detailed model; suitable low-order models of appropriate complexity or order can be derived to fit these input-output responses using system identification techniques. Perturbation of one input at a time, as desired, is possible; step or other suitable disturbance in the particular input may be initiated and corresponding response of selected input may be initiated and corresponding response of selected output obtained. Unlike field testing, the input-output data do not suffer from noise or measurement lags. These features render the identification process easier, leading to simplified algorithms.

These advantages of a detailed physical model are exploited in this research work wherein lower order models are derived for all dynamically
significant subsystems of a 500 MW power plant loop. The input-output models of these low-order models include most of the process variables of interest to power plant operation.

4.3. SYSTEM DESCRIPTION

The lower order dynamic models of the dynamically significant subsystem of a typical 500 MW pulverized coal-fired thermal power plant in BHEL, Hyderabad is presented in this section. The schematic of the 500 MW power plant cycle is shown in Fig. 4.1.

Fig. 4.1. Schematic of a 500 MW Thermal Power Plant

It is a reheat-regenerative cycle and the boiler is of the drum type, with controlled circulation. The condensate pumps draw the condensate water
from the condensate hot well. The condensate water then flows through the Low Pressure Heater Stages to the deaerator, thereby picking up enthalpy. Under saturated condition, the condensate is deaerated by steam that flows in the deaerator. From the deaerator feed storage tank, the Boiler Feed Pumps draw the feed water and pump it through the High Pressure Heater Stages. It is then passed on to the Economizer stage in the boiler from where it flows to the boiler drum. In both these stages, the feed water picks up heat.

Water that is stored in the boiler drum begins to circulate through the downcomer and waterwall tubes by the process of natural convection. During this stage, it picks up radiant heat from the furnace through the waterwalls. The steam in saturated condition now flows through the super-heater stages gaining superheat. The final temperature is controlled by the attemperator spray flow.

The steam in the superheated state is admitted to the High Pressure Turbine. The exhaust steam from the High Pressure Turbine goes back to the reheater. In the Reheater stage, the temperature is raised to the original level, while the attemperator spray is being used for temperature control. The reheated steam is further admitted to the Intermediate Pressure (IP) Turbine and then to the Low Pressure (LP) Turbine. Exhaust steam from the LP turbine goes back to the condenser and the cycle repeats. The significant subsystems of the power plant are Boiler Feed Pump (BFP), High Pressure (HP) Heater, Economizer, Circulation System, Super-heater, HP and IP Turbine, Reheater, Condenser, Condensate pump, LP Heater, Deaerator and Furnace.

The steps involved in the low-order modeling of the subsystems are obtained and illustrated by considering the circulation system. These low-order
models can be implemented in hardware and in a training simulator. The following sections describe the methodology and principle behind lower order modeling of the circulation system of the 500 MW boiler.

The detailed model of the circulation system is quite non-linear. It consists of coupled non-linear differential equations associated with algebraic equations for heat transfer and steam-water properties. These equations can be used to compute the changes in the drum pressure and drum level for any changes in the input variables. Around a given steady state, say the full-load operating point, the incremental changes in the inputs and outputs can be linearly related and the circulation system can be characterized by

\[
\begin{bmatrix}
G_{11} & G_{21} & G_{31} & G_{41} \\
G_{12} & G_{22} & G_{32} & G_{42}
\end{bmatrix}
\begin{bmatrix}
\Delta T_{weco} \\
\Delta W_{weco} \\
\Delta Q_{gww} \\
\Delta W_{sdro}
\end{bmatrix} =
\begin{bmatrix}
\Delta P_{DR} \\
\Delta V_{DR}
\end{bmatrix} \quad (4.1)
\]

Where \( G_{xi}(s) \) is the transfer function relating the output at port \( x \) to the input at port \( i \).

Thus, the circulation system is perceived as a multi-input multi-output system as shown in Fig. 4.2.
The inputs to the circulation system are

- Feed water Temperature at the Economizer outlet. - $T_{WECO}$
- Feed water flowrate at the Economizer outlet. - $W_{WECO}$
- Heat flow rate to water walls. - $Q_{GW}$
- Steam flow rate from drum. - $W_{SDRO}$

The output from the circulation system is

- Drum Pressure - $P_{DR}$

The black box model approach has been used to develop the lower order model of the circulation system. The responses are generated from the validated model of the 500 MW power plant available at BHEL, Hyderabad. The system may be considered to behave linearly for small input variations around a steady state operating point. Therefore, the inputs and outputs can be related by suitable transfer functions that are derived from the input-output data of the circulation system.
In this research work, the relationship between the input and output parameters of the circulation system are modeled as transfer functions whose parameters are identified using system identification techniques. For this purpose, the circulation system is assumed to be a MIMO system which has multiple inputs and outputs out of which the drum pressure output is used for further analysis.

Fig. 4.3 Transfer function model of Input Vs Drum Pressure

There are many system identification techniques available in literature for deriving the order and parameters of the subsystem. Walsh function is one such methodology which works well even with unknown initial conditions. But, in the proposed methodology, it is observed that the behavior of input and outputs are quite simple and the general form of transfer function can be estimated with ease just by inspection of the input output curves. Once the order is known, then the other parameters like gain, poles and zeros can be
easily determined. Software Simulated system identification tool box in Matlab has been used to estimate the parameters.

4.4 SYSTEM IDENTIFICATION

Science is all about inferring models from observations and studying their properties. System Identification, therefore deals with the problem of developing mathematical models of dynamic systems based on observations from the systems. The models may be in various forms and with varying degrees of freedom. In daily life, many systems are dealt with mental models which do not involve any mathematical formalization at all. For certain systems, it deems fit to describe its characteristics using numerical tables and graphs. Such models are called graphical models. For more sophisticated systems, it is necessary to use differential or difference equations to describe the relationship between the input and output variables of a system. These are called mathematical models or analytical models. These models are largely instrumental for simulation and prediction and is extensively used in all fields.

The procedure for modeling is quite application dependent. The development of a model from data involves three basic entities.

- The data
- A set of candidate models
- A rule by which the candidate models can be assessed using the data.
The input output data are obtained from experiments conducted on the system. A set of candidate models is then obtained. This is the most critical part of the system identification procedure. It is here that a priori knowledge and engineering intuition and insight are combined to arrive at well-established relationships that characterize the system being modeled. The identification method now helps in determining the best model in the set. The model is later validated which involves various procedures to assess how the model relates to the observed data, to prior knowledge and to its intended use.

When formulating and solving an identification problem, it is important to have the purpose of the identification in mind. Even if the purpose of identification is to design a control system, the character of the problem might vary widely depending on the nature of the control problem. The choice of the model structure is one of the basic ingredients in the formulation of the identification problem. If classical controller design techniques are to be used, the model can be characterized by a transfer function or by an impulse response. As the power plants adopt the classical PID controller design for the control loops, it is sufficient to characterize the circulation system by set of transfer functions, the system being a Multi Input Multi Output one.

This research work uses the detailed mathematical model to generate input output data and hence identify the parameter values. It may be noted from Eq. (4.1) that when only one input ‘i’ is excited and the other inputs are zero, the output at port x is given simply by Eq. (4.2)

\[
\frac{\text{Output } x}{\text{Input } i} = G_{xi}
\]  

(4.2)
all quantities in Eq. (4.2) being expressed in Laplace variable form. Hence if the output ‘x’ response is available for a step change in input ‘i’, with the other inputs being zero, \( G_{xi} \) can be determined. As a specific case, let us consider the evaluation of the transfer function \( G_{41} \) between \( \Delta P_{DR} \) and \( \Delta W_{sdro} \). From the detailed circulation system model, the variation of pressure \( P_{DR} \) for a small step change in the steam flow rate \( W_{sdro} \) alone is obtained as shown in Fig. 4.4 d. The drum pressure response for a step increase in each of the four input variables is observed. The graphs have been plotted against time in seconds as shown in Fig. 4.4.a to Fig. 4.4.d.

**Fig. 4.4.a. Drum Pressure Response for a step change in Feed water Temperature at Economizer outlet (\( \Delta T_{we\text{co}} \))**

The variation in the drum pressure, \( P_{DR} \) for a step change of magnitude 15° C in the feed water temperature at economizer outlet, \( T_{WECO} \) has been obtained from the detailed mathematical model. These values are plotted against time as shown in Fig. 4.4.a. The step response obtained indicates that the system function between the input and output variables is an integrating system. This is in conformity with the physics of the process, because an increase in the temperature of the feed water at the economizer outlet increases
the drum pressure. The Laplace transform of an integrating system takes the general form \( \frac{K}{s} \). The task of system identification now reduces to finding the value of the gain \( K \). The transfer function relating the input and output is represented in Eq. 4.3

\[
\frac{\Delta P_{DR}(s)}{\Delta T_{weco}(s)} = G_{11}(s) = \frac{K_1}{s} \tag{4.3}
\]

where \( K_1 \) – gain of the system

Secondly, the response of the circulation system in the form of drum pressure, \( P_{DR} \) to a step change of magnitude 10 tons/hour in the feed water flowrate at the Economizer outlet, \( \Delta W_{weco} \) is obtained from the detailed mathematical model. These values are plotted against time as shown in Fig. 4.4.b. By observing the step response obtained, it may be inferred that the system function between the input and output variables is an integrating system. This is due to the increase in drum pressure caused by an increase in the flowrate of water circulated into the drum from the economizer outlet. The Laplace transform of an integrating system takes the general form \( \frac{K}{s} \). The task of system identification now reduces to finding the value of the gain \( K \). The transfer function relating the input and output is represented in Eq.(4.4)

\[
\frac{\Delta P_{DR}(s)}{\Delta W_{weco}(s)} = G_{21}(s) = \frac{K_2}{s} \tag{4.4}
\]

where \( K_2 \) – gain of the system
Thirdly, the characteristics of the circulation system to a step change of magnitude $40 \times 10^3$ Kcal/sec in the heat gained by the water walls due to the combustion of pulverized coal inside the furnace in the presence of primary and secondary air is studied by observing the drum pressure output. The step response characteristics as shown in Fig. 4.4.c portray that system function between the input and output variables is an integrating system.
This is due to the increase in drum pressure caused by an increase in the flowrate of water circulated into the economizer inlet. The Laplace transform of an integrating system takes the general form \( \frac{K}{s} \). The task of system identification now reduces to finding the value of the gain \( K \). The transfer function relating the input and output is represented in Eq. 4.5.

\[
\frac{\Delta P_{DR}(s)}{\Delta Q_{gww}(s)} = G_{31}(s) = \frac{K_3}{s} \tag{4.5}
\]

where \( K_3 \) – gain of the system

Finally, the drum pressure response of the circulation system to a step change in the outlet flow rate of steam from the drum is obtained. Though the steam outlet flowrate is the output of the drum, it can be treated as an input to the drum because it affects the drum pressure. The values are obtained from the detailed mathematical model and plotted against time as shown in Fig. 4.4.d. The characteristics indicates that the system is an integrating one but has a negative slope. This is due to the fact that the drum pressure decreases with an increase in the steam flow output from the drum.

![Fig. 4.4.d. Drum Pressure Response for a step change in Steam outlet from drum (\( \Delta W_{sdro} \))](image-url)
The transfer function relating the input and output is represented in Eq. 4.6

\[ \frac{\Delta P_{DR}(s)}{\Delta W_{sdr}(s)} = G_{41}(s) = \frac{K_4}{s} \]  

(4.6)

where \( K_4 \) – gain of the system.

Now, by using the gradient search technique of system identification in simulation software, the system gain is estimated. Theoretically, gradient descent algorithm is one that is used to minimize functions. Given a function defined by a set of parameters, gradient descent starts with an initial set of parameter values and iteratively moves toward a new set of parameter values that minimize the function. This iterative minimization is achieved by taking steps in the negative direction of the function gradient. The screen shot of the identification tool used to estimate the gain is shown in Fig. 4.5.

![Fig. 4.5 Identification tool used for System Identification](image)
The estimated system parameters are tabulated in Table 4.1.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>TF Model</th>
<th>TF Structure</th>
<th>Parameter Identified</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$G_{11}(s)$</td>
<td>$\frac{K}{s}$</td>
<td>0.17719</td>
</tr>
<tr>
<td>2</td>
<td>$G_{21}(s)$</td>
<td>$\frac{K}{s}$</td>
<td>0.0013798</td>
</tr>
<tr>
<td>3</td>
<td>$G_{31}(s)$</td>
<td>$\frac{K}{s}$</td>
<td>$2.1007 \times 10^{-6}$</td>
</tr>
<tr>
<td>4</td>
<td>$G_{41}(s)$</td>
<td>$\frac{K}{s}$</td>
<td>$-7.22 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

From inspection of the values of K obtained using the system identification tool, it may be observed that the values are in conformity with the physics of the process and behave exactly like the detailed mathematical model. This may be verified by observing the value of K for the transfer functions represented by $G_{41}(s)$ which represents the input-output relationship between the drum pressure $P_{DR}$ and Steam outlet from drum $W_{sdro}$. The response obtained using the detailed mathematical model represents a negative slope characteristics. This is due to the fact that the pressure in the drum decreases with an increase in steam outlet flow from the drum. This characteristic of the transfer function is exhibited by the lower order model obtained by system identification as well. The determined value of K is negative, which proves the fact that the characteristics of the system remains unaltered, due to lower order modeling.
4.5 SIMULATION OF LOWER ORDER MODEL OF CIRCULATION SYSTEM

The transfer function thus obtained are simulated for step changes in the input variables and the output is noted. By observing the response curves of drum Pressure $P_{DR}$ for step changes in the input variable. It may be noted that the transfer function relates to the behavior of the system. The required transfer functions thus obtained can be used for control and simulation studies of the circulation system and further be integrated with the lower order models of the other subsystems to obtain a complete lower order model of a thermal power plant.

4.6 CONCLUSION

This chapter aims at emphasizing the usefulness of mathematical model in obtaining the lower order model of a circulation system. The required input and output data pertaining to circulation system are accurately generated from the detailed mathematical model of the 500 MW plant. The lower order system parameters are evaluated from these data by employing conventional system identification tool box. The transfer functions obtained can be used for dynamic stability analysis of the system. This methodology can be extended to other subsystems as well.