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Linearization of Model Based Nonlinear Boiler – Turbine Control System

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ABSTRACT: This paper presents the application of state space model and controller design to a drum-type boiler–turbine system. The step-response of a state space model is developed with the linearization of the nonlinear plant model. Then, the control performance of the model is based on the PID controller. Because of severe nonlinearity of drum water-level dynamics, it is observed that the simulation with the response of the closed loop system using PID controller is more efficient than open loop system.

KEYWORDS*:* Boiler-turbine control, state space model, linearization, PID controller, process control.

I. INTRODUCTION

There are dramatic changes in the power industry because of deregulation. One consequence of this is that the demands for rapid changes in power generation are increasing. This leads to more stringent requirements on the control systems for the processes. It is required to keep the processes operating well for large changes in the operating conditions. One way to achieve this is to incorporate more process knowledge into the systems. This report presents a nonlinear model for steam generation systems in boiler which are a crucial part of most power plants. The severe nonlinearity and wide operation range of the boiler plant have resulted in many challenges to power system control engineers.Mica properties over a wide operating range. But, one reason is that the control problems in boiler is difficult because of the complicated shrink and swell dynamics. This creates a nonminimu0m phase behavior which changes significantly with the operating conditions. This boiler–turbine system is usually modeled with a multi-input–multi-output (MIMO) nonlinear system. The severe nonlinearity and wide operation range of the boiler–turbine plant have resulted in many challenges to power system control engineers. Control systems must be able to model dynamic systems in mathematical terms and analyze their dynamic characteristics.

A mathematical model of a dynamic system is defined as a set of equations that represents the dynamics of the system accurately, or at least fairly well. Note that a mathematical model is not unique for any given system. A system may be represented in many different ways and, therefore, may have many mathematical models, depending on one's perspective. Mathematical models may assume many different forms. Depending on the particular system and the particular circumstances, one mathematical model may be better suited than other models. For example, in optimal control problems, it is advantageous to use state-space representations. On the other hand, for the transient-response or frequency-response analysis of single-input single-output, linear, time-invariant systems, the transfer function representation may be more convenient than other representation. Once a mathematical model of a system is obtained, various analytical and computer tools can be used for analysis and synthesis purposes. In our proposed work we are going to model the boiler turbine system using state space model. There has also been a significant development of methods for mathematical modelling, we referred Un-Chul Moon and Kwang. Y. Lee, Life Fellow (2009) for mathematical modelling, linearization and non-linearization of the boiler-turbine system.

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II. BOILER-TURBINE SYSTEM

The two major operations in the boiler-turbine system are generation of steam by heating the water into steam. The steam is heated further to obtain super steam for maximum power generation and to reduce wastage of steam. The general block diagram for the boiler-turbine system and its operation is shown in fig.1

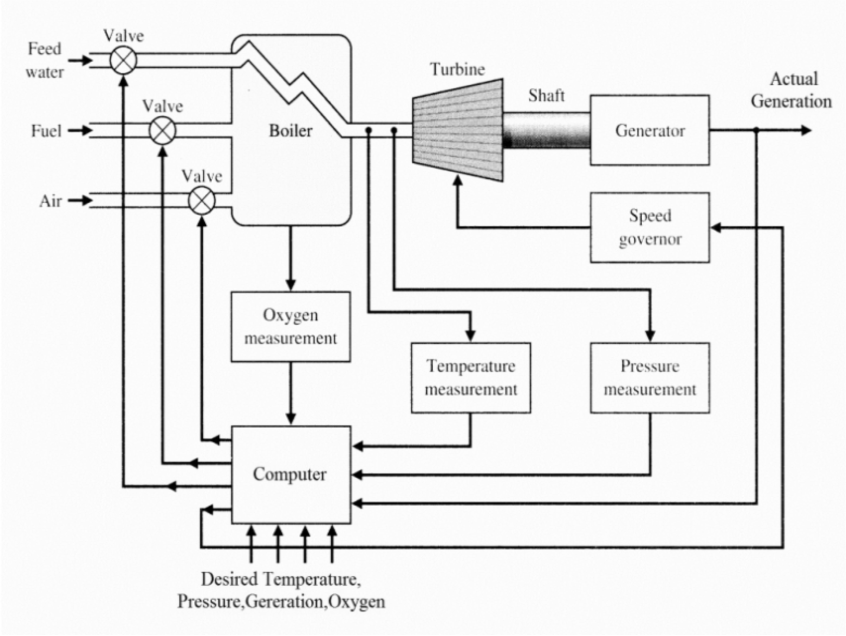


Fig.1 Block diagram for the boiler-turbine system

The steam is used to rotate the turbine for creating mechanical energy. The turbine is rotated in a magnetic field to obtain the magnetic lines of force. The steam which is a conducting device when cuts the magnetic lines of force created in the turbine induces power.

III. NONLINEAR MODEL

The model of Bell and Astrom is taken as a real plant among various nonlinear models for the boiler–turbine system. The model represents a boiler-turbine generator for overall wide-range simulations and is described by a third-order MIMO nonlinear state equation. The three state variables are Drum steam pressure, Electric power, Steam water fluid density in the drum, respectively. The three outputsare drum steam pressure, electric power, and drum water-level deviation, respectively. Thedrum water-levelis calculated using two algebraic calculations that are the steam quality and the evaporation rate respectively. The three inputs are normalized positions of valve actuators that control the mass flow rates of fuel, steam to the turbine, and feed water to the drum, respectively. Positions of valve actuators are constrained to [0, 1], in their rate of change per second. The equation (1) to (8) is non-linear boiler turbine state equation.

$$\dot{x}_1 = -0.0018u_2x_1^{9/8} - 0.9u_1 - 0.15u_3 \quad (1)$$

$$\dot{x}_2 = \frac{\left[(0.73u_2 - 0.16)x_1^{9/8} - x_2\right]}{10} \qquad (2)$$

$$\dot{x}_3 = \frac{[141u_3 - (1.1u_2 - 0.19)x_1]}{85} \qquad (3)$$

$$y_1 = x_1 \qquad (4)$$

$$y_2 = x_2 \qquad (5)$$

$$y_3 = 0.05\left(0.13073x_3 + 100a_{cs} + \frac{q_e}{9} - 67.975\right) \qquad (6)$$

$$a_{cs} = \frac{[(1 - 0.001538x_3)(0.8x_1 - 25.6)]}{x_3(1.0394 - 0.0012304x_1)} \qquad (7)$$

$$q_e = (0.854u_2 - 0.147)x_1 + 45.59u_1 - 2.514u_3 - 2.096 \qquad (8)$$

Where,

The three inputs are
u_1=Normalized positions of valve actuators that control the mass flow rates of fuel
u_2= Normalized positions of valve actuators that control the steam to the turbine
u_3= Normalized positions of valve actuators that control feed water to the drum
The three outputs are
y_1 = Drum steam pressure (x_1)
y_2 = Electric power (x_2)
y_3 = Drum water-level deviation (L in meters)
The y_3, drum water-level L, is calculated using two algebraic calculations
a_{cs}= *Steam* quality (mass ratio)
q_e = Evaporation rate (kilograms per second)
The three state variables are
x_1 = Drum steam pressure (P in Kg/cm^2)
x_2= Electric power (E in Megawatt)
x_3= Steam water fluid density in the drum (ρfin Kg/m^2)

IV. LINEARIZED MODEL

In most cases of designing boiler–turbine control systems, it is assumed that the exact mathematical model is given; therefore, the linearization of the nonlinear mathematical model is used to design the linear controller. The nonlinear model is linearized using Taylor series expansion at the operating point, $y_0 = (y_{10}, y_{20}, y_{30})$, $x_0 = (x_{10}, x_{20}, x_{30})$, $u_0 = (u_{10}, u_{20}, u_{30})$.
The result of linearization is as follows:

$$\dot{\bar{x}} = A\bar{x}(t) + B\bar{u}(t) \qquad (9)$$

$$\bar{y}(t) = C\bar{x}(t) + D\bar{u}(t) \qquad (10)$$

Where,

$$A = \begin{bmatrix} -\frac{0.0162}{8}u_{20}x_{10}^{1/8} & 0 & 0 \\ \left(\frac{6.57}{80}u_{20} - \frac{1.44}{80}\right)x_{10}^{1/8} & -\frac{1}{10} & 0 \\ \left(\frac{0.19}{85} - \frac{1.1}{85}u_{20}\right) & 0 & 0 \end{bmatrix} \qquad (11)$$

$$B = \begin{bmatrix} 0.9 & -0.0018x_{10}^{9/8} & -0.15 \\ 0 & -\frac{0.73}{10}x_{10}^{9/8} & 0 \\ \left(\frac{0.19}{85} - \frac{1.1}{85}u_{20}\right) & -\frac{1.1}{85}x_{10} & \frac{141}{85} \end{bmatrix} \qquad (12)$$

$$C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ \left(5\frac{\partial a_{cs}}{\partial x_1} + \frac{1.1}{9}\frac{\partial q_e}{\partial x_1}\right) & 0 & \left(0.065 + 5\frac{\partial a_{cs}}{\partial x_3}\right) \end{bmatrix} \quad (13)$$

$$D = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0.2533 & 0.00474x_{10} & -0.014 \end{bmatrix} \quad (14)$$

The variables y, x, and u are the differences of the output, state, and input, respectively from the corresponding operating points. The operating points are determined based on a nominal operation of the plant. Considering that the model represents a 210 MW unit, the operating point for power output $y_2$is 210 MW. This yields the corresponding pressure y_1 as 143 kg/cm$_2$from the balance of the plant model. The operating point for water level y_3 must be zero in order to keep the water level in the middle of the drum, which is 50% in the drum level. Then, the operating points for other remaining variables can be calculated by neglecting the derivative terms in (1) - (9). The resulting operating points are $y_0 = (143, 210, 0)$, $x_0 = (143, 210, 402.759)$, $u_0 = (0.2, 0.7, 0.4)$.

The constant matrices A, B, C, and D are evaluated at these operating points as follows:

$$A = \begin{bmatrix} -0.0026 & 0 & 0 \\ 0.0735 & -0.1000 & 0 \\ -0.0068 & 0 & 0 \end{bmatrix} \quad (15)$$

$$B = \begin{bmatrix} 0.9000 & -0.4787 & -0.1500 \\ 0 & 19.4120 & 0 \\ 0 & -1.8500 & 1.6588 \end{bmatrix} \quad (16)$$

$$C = \begin{bmatrix} 1.0000 & 0 & 0 \\ 0 & 1.0000 & 0 \\ 0.0062 & 0 & 0.0033 \end{bmatrix} \quad (17)$$

$$D = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0.2533 & 0.6778 & -0.0140 \end{bmatrix} \quad (18)$$

Then, a simple algebraic operation with Laplace transform gives transfer functions as follows:

$$\mathrm{Y(s)} = [\mathrm{C(sI - A)^{-1}B + D}]\mathrm{U(s)} \quad (19)$$

$$\mathrm{Y(s)} = \begin{pmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{pmatrix} U(s) \quad (20)$$

TRANSFER FUNCTION MATRIX

The transfer function matrix is obtained by the MATLAB coding where the A, B, C, D Matrix are used. The output of the coding is obtained as the transfer function matrix of 3X3 matrix.

$$G_{11} = \frac{0.9}{s + 0.002635} \quad (21)$$

$$G_{12} = \frac{-0.4787}{s + 0.002635} \quad (22)$$

$$G_{13} = \frac{-0.15}{s + 0.002635} \quad (23)$$

$$G_{21} = \frac{0.0661}{\mathrm{s}^2 + 0.1026\,\mathrm{s} + 0.0002635} \quad (24)$$

$$G_{22} = \frac{19.41\,\mathrm{s} + 0.01599}{\mathrm{s}^2 + 0.1026\,\mathrm{s} + 0.0002635} \quad (25)$$

$$G_{23} = \frac{-0.01102}{s^2 + 0.1026\,s + 0.0002635} \tag{26}$$

$$G_{31} = \frac{0.2533\,s^2 + 0.006232\,s - 2.045e^{-005}}{s^2 + 0.002635\,s} \tag{27}$$

$$G_{32} = \frac{0.6778\,s^2 - 0.007334\,s - 5.358e^{-006}}{s^2 + 0.002635\,s} \tag{28}$$

$$G_{33} = \frac{-0.014s^2 + 0.004559\,s - 1.796e^{-005}}{s^2 + 0.002635\,s} \tag{29}$$

With (21) - (29), the unit step-response modelis developed, whereG_{ij}represents the response $y_i$and input u_j. The boiler model will help to analysis the whole operation of the boiler system. Hence boiler was mathematically modelled which is future used for control the process by different technique.

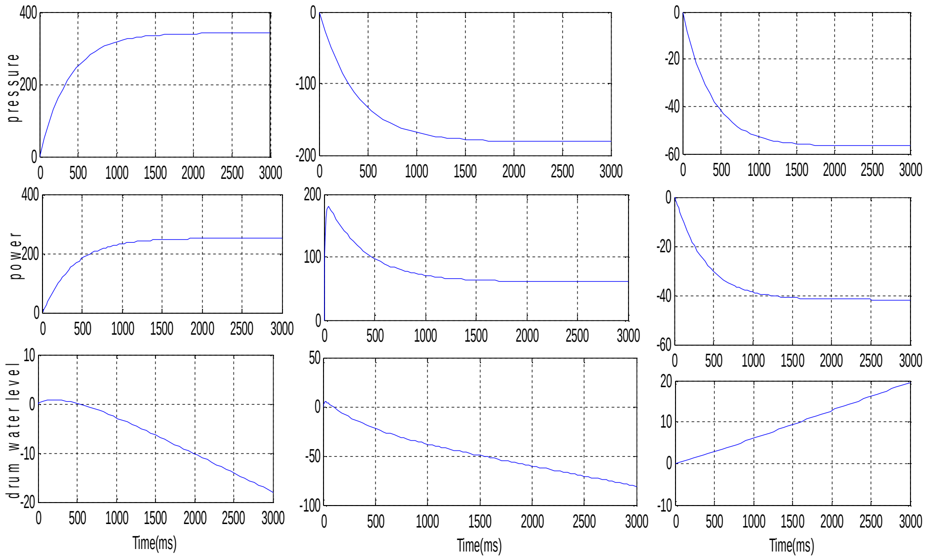
V. PID CONTROLLER

The PID controller calculation (algorithm) involves three separate constant parameters, and is accordingly sometimes called three-term control: the proportional, the integral and derivative values, denoted P,I, and D.Heuristically, these values can be interpreted in terms of time: P depends on the present error, I on the accumulation of past errors, and D is a prediction of future errors, based on current rate of change. The one of the heuristic tuning method is formally known as the Ziegler–Nichols method. Z–N tuning creates quarter wave decay. This is an acceptable result for some purposes, but not optimal for all applications The K_i and K_d gains are first set to zero. The *P* gain is increased until it reaches the ultimate gain, K_u at which the output of the loop starts to oscillate. K_u and the oscillation period P_u.

VI. RESULTS AND DISCUSSIONS

A. OPEN LOOP RESPONSE FOR THE TRANSFER FUNCTIONS G_{ij}

The three columns of plots are the responses corresponding to the respective step inputs, u_1, u_2, and u_3. Responses for open loop individual transfer function of the matrix given in the fig.2.



u_1 u_2 u_3

Fig.2 Step-responses of linearized model

Step-responses of linearized model Horizontal axes are time (in seconds), and the three rows of plots represent the outputs, y_1(P in kg/cm$_2$), y_2(E in megawatt), and y_3(L in meters).

B. SIMULINK MODEL OF OPEN LOOP SYSTEM

The state space matrix is given in MATLAB with the step input of the boiler. The open loop response of the three output response is shown in the fig.3.

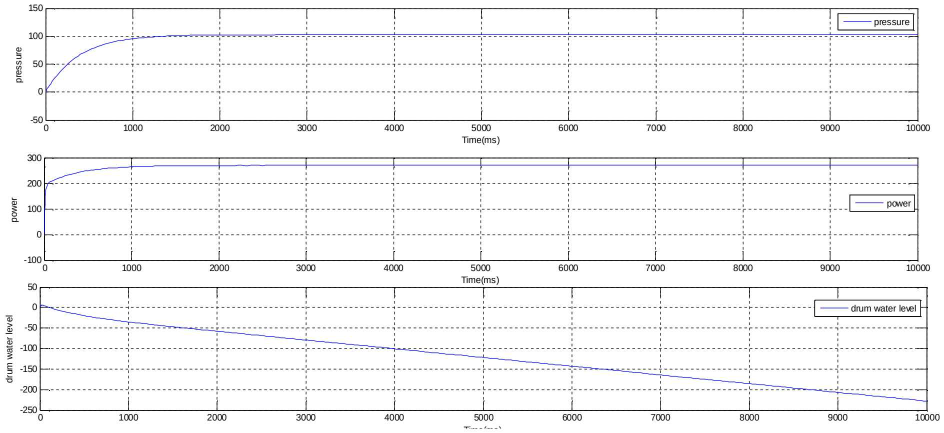


Fig.3 Response of open loop system

The response of three parameter is get settled but not at the desired value. Thereby there is the need of closed loop system with a controller for control the value at the desired value and settle the output at short time with minimum overshoot.There are so many drawbacks, so we are going for closed loop system to obtain desired output in an excellent method.

C. SIMULINK MODEL OF CLOSED LOOP SYSTEM

The state space matrix is given in MATLAB with the set point for the closed loop system of the boiler with PID controller. The Ziegler–Nichols method is use for tuning the controller. The response of the closed loop PID controller is shown in the fig.4 which is used to study the plant model.

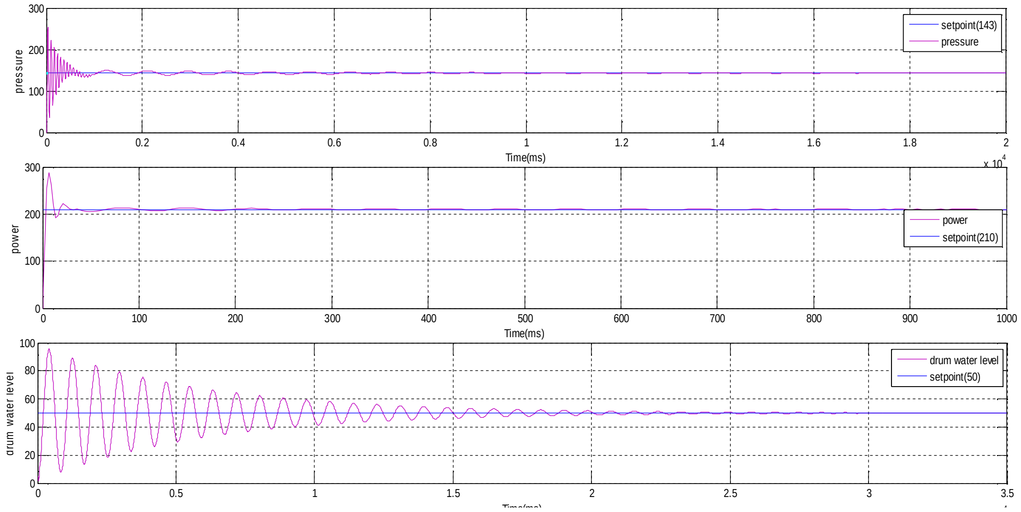


Fig.4 Response of closed loop system

The response of PID controller in MIMO boiler system, we have absorbed that the settling time of y_1(P in kg/cm$_2$) in 20,000msec, y_2(E in megawatt) in 500msec, and y_3(L in meters) in 32,000msec.

VII. CONCLUSION

A nonlinear physical model with a complexity that is suitable for model-based control has been presented. The model is based on physical parameters for the plant and can be easily scaled to represent any drum power station. The controller for the boiler is conventional PID controller which is regularly in use. For more performance and robustness of the control system can further be improved by using advanced control techniques like Model Reference Adaptive Control, Optimal Control Technique, Model Predictive Control, etc.

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