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Design and Control of Ideal Decoupler for Boiler Turbine 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 PID controller is based on ideal decouple and multivariable system of the boiler. Because of several nonlinearity of drum water-level dynamics, it is observed that the simulation with the response of the decoupled PID controller is more efficient than decentralized PID controller.***

Keywords: Boiler–turbine control, state space model, linearization, ideal decouple, PID controller, process control.

1. 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 [1]. 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 [2].

The goal is to develop moderately complex nonlinear models that capture the key dynamical 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 non-minimum 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 [3]-[5]. 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 [1].

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 modeling; we referred Un-Chul Moon and Kwang. Y. Lee, Life Fellow (2009) for mathematical modeling, linearization and non-linearization of the boiler-turbine system [4].

Boiler system is a MIMO system with more loop interaction. To avoid loop interactions, MIMO systems can be decoupled into separate loops known as single input, single output (SISO) systems. Decoupling may be done using several different techniques, including restructuring the pairing of variables, minimizing interactions by detuning conflicting control loops, opening loops and putting them in manual control, and using linear combinations of manipulated and/or controlled variables. If the system can’t be decoupled, then other methods such as neural networks or model predictive control should be used to characterize the system. The decouple by ideal matrix technique is used in our paper [9]. The decouple method is referred from Them, M.T (1999) and also many other papers for more detail.

2. Boiler-Turbine System

The general block diagram for the boiler-turbine system and its whole operation is shown in the fig.1.

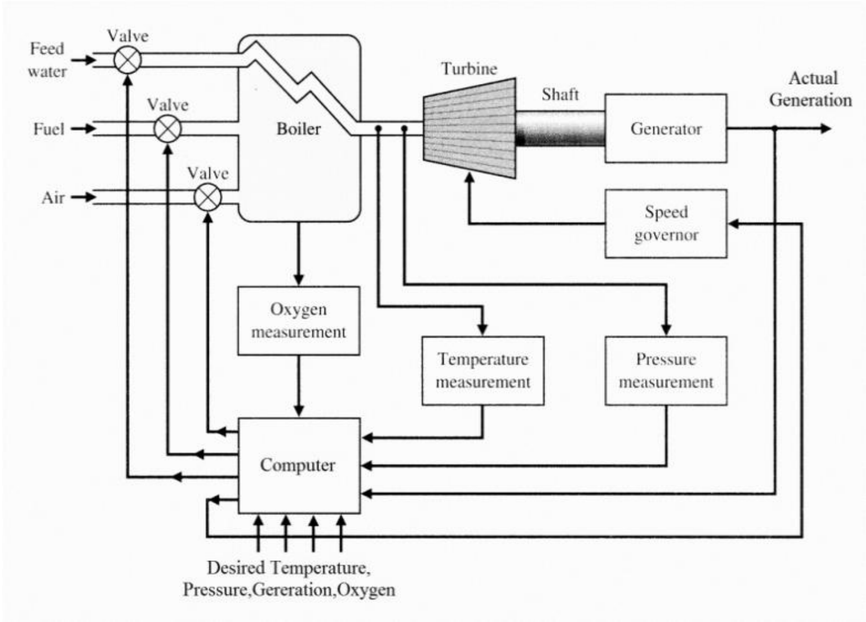

Figure 1: Block diagram for the boiler-turbine system

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 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.

3. 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 [13]. Positions of valve actuators are constrained to [0, 1], in their rate of change per second. The equation (3.1) to (3.8) is non-linear boiler turbine state equation.

$$\dot{x}_1 = -0.0018u_2 x_1^{9/8} - 0.9u_1 - 0.15u_3 \quad (1)$$

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

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

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

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

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

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

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

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 (ρf in Kg/m^2)

4. 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:

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

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

Where,

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

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

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

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

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:

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

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

5. 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.

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

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

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

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

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

$$G_{23} = \frac{-0.01102}{\mathrm{s}^2 + 0.1026\,\mathrm{s} + 0.0002635} \quad (26)$$

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

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

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

With (21)–(29), the unit step-response modelis developed, where G_{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.

6. Design of Decoupler

The decoupler is designed to reduce the interactions to the maximum in the multivariable measurement like boiler. The decoupling matrix is obtained to make the interaction system to non-interaction system and reduce the uncertain.

$$D = \begin{bmatrix} D_{11} & D_{12} & D_{13} \\ D_{21} & D_{22} & D_{23} \\ D_{31} & D_{32} & D_{33} \end{bmatrix} \quad (30)$$

According to ideal decoupling procedure the diagonal is Substituted as $D_{11}=D_{22}=D_{33}=1$ in equation(30).

Multiply the G matrix which is the transfer function matrix with the D matrix to obtain all the value of GD matrix. GD diagonal matrix gives the SISO system of three variables which is to be control in the boiler.

$$\mathrm{G*D} = \begin{bmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{bmatrix} \begin{bmatrix} 1 & D_{12} & D_{13} \\ D_{21} & 1 & D_{23} \\ D_{31} & D_{32} & 1 \end{bmatrix} \quad (31)$$

For an ideal GD matrix non-diagonal equation is equal to zero so that the equation of D_{12}, D_{13}, D_{21}, D_{23}, D_{31}, and D_{32} can be obtained. Apply the D matrix equation in GD matrix to get the diagonal value of GD matrix which is nothing but the three SISO to control the three output variables.

$$\mathrm{GD}_{11} = \frac{0.49291s^3 + 0.09907s^2 + 0.17153s + 0.12128}{0.27174s^4 + 0.09502s^3 + 0.2352s^2 + 0.000666s} \quad (32)$$

$$GD_{22} = \frac{0.49291s^3 + 0.09938s^2 + 0.17153s + 0.21}{0.0254s^4 + 0.0578s^3 + 0.03627s^2 + 0.00369s} \quad (33)$$

$$GD_{33} = \frac{0.49291s^3 + 0.0628s^2 + 0.17205s + 0.00151}{17.469s^3 + 0.09206s^2 + 0.0012s} \quad (34)$$

Thereby the SISO of pressure, power and level system is obtain by the diagonal equation of GD matrix.

7. 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.

8. Results And Discussions

8.1 Open Loop Response for the Transfer Functions

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). 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.1.

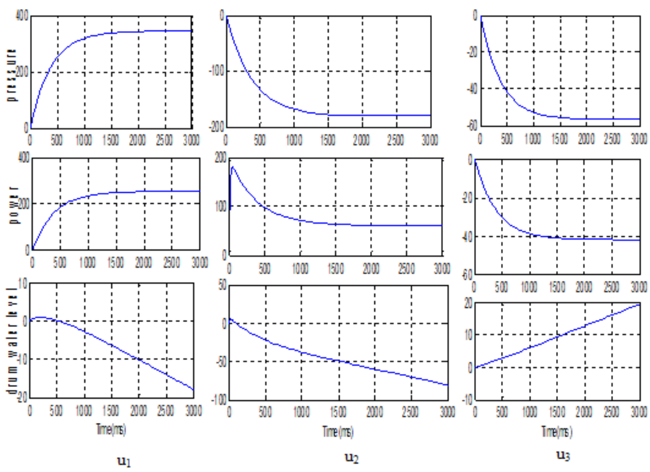

Figure 2: Step-responses of linearized model

8.2. 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.2. 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.

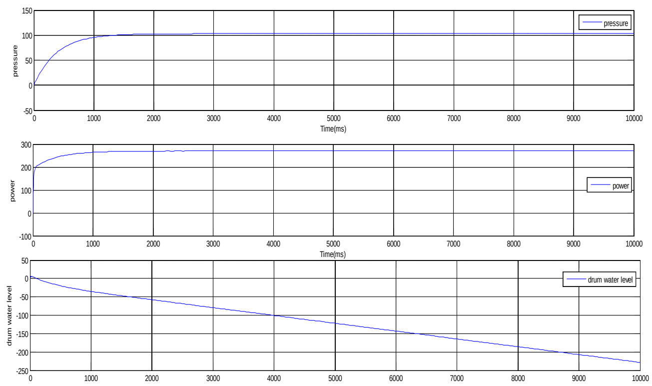

Figure 3: Response of open loop system

There are so many drawbacks, so we are going for closed loop system to obtain desired output in an excellent method

8.3. Simulink Model of Decenterlized PID Controller

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.3 which is used to study the plant model.

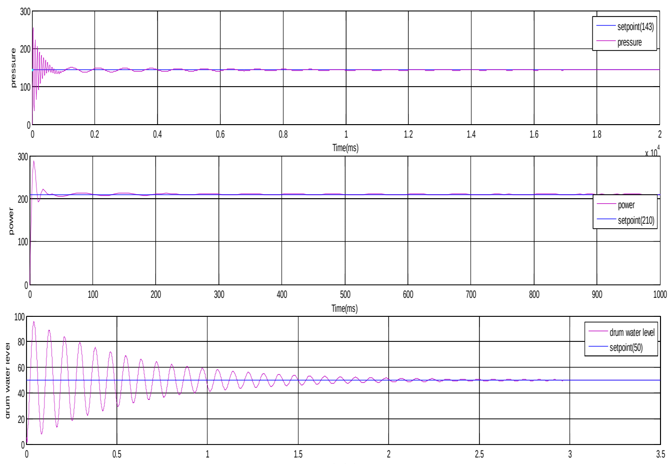

Figure 4: Response of closed loop system

From the fig.5 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.

9. Simulink Model of Decouple PID Controller

The simulation of each SISO system of boiler is design using simulink model in MATLAB.

9.1. Pressure Control

Closed loop simulink model for GD_{11} which is pressure as output. The set point of the pressure is 143 kg/cm^2.The PID controller was tuned by Ziegler-Nichlos Method there by the gain is obtained.

K_p=Proportional Gain=0.2514

K_i=Integral Gain=0.040224

K_d= Derivative Gain=0.3928125

The closed loop response of the SISO system of pressure control in fig.5 was obtained from the simulink model for SISO system to control pressure in the boiler.

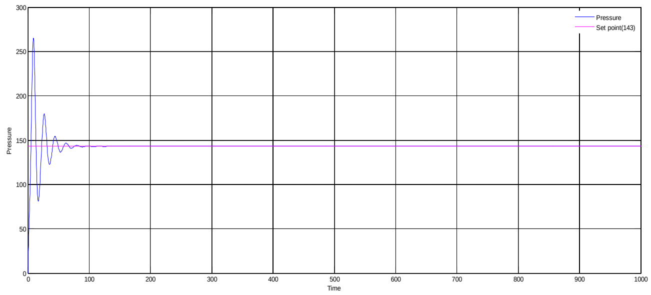

Figure 5: Closed loop response of the SISO system of pressure

The presure is to be settle at 143 kg/cm^2. In interacting system peak overshoot is high and settling time taken for pressure also high which is observed from the fig.4. The settling time for pressure is 20,000 ms. Non-interacting response for the pressure from the fig.5 shows the settling time for the closed loop response of pressure as minimised to 85 ms and the peak overshoot also get reduced.

9.2. Power Control

Closed loop simulink model for GD_{22} which is power as output form the decoupler of the boiler. The set point is 210, because the total output power of the plant is 210 MW.The PID controller was tuned by Ziegler-Nichlos Method and the gain of P,I,D also obtained.
K_p=Proportional Gain=0.0102
K_i=Integral Gain=0.00102
K_d= Derivative Gain=0.0153

The closed loop response of the SISO system of power control in the boiler in fig.6 was obtain from simulink model for SISO system to control power in the boiler.

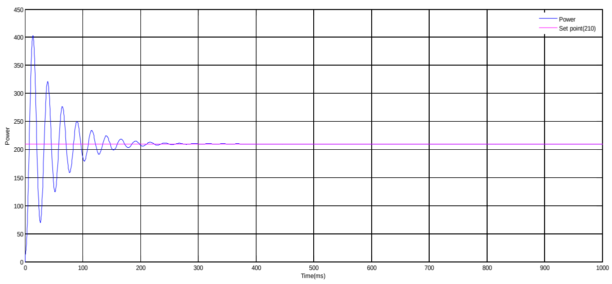

Figure 6: Closed loop response of the SISO system of power

The power should settle down at 210. Because the output of Tuticorin Thermal Power Station is 210MW. so, it is given as set point. In interacting system peak overshoot is high and settling time(500ms) taken also high for power which is observed from the fig.4. The settling time for power is 310ms in Non-interacting response for the power from the fig.6 shows the settling time for the closed loop response of power as minimised from 500ms to 310ms and the peak overshoot also get reduced.

9.3. Level Control

Closed loop simulink model for GD_{33} which is power as output form thedecoupler of the boiler. The set point is 50% of the drum level which is 0 cm . So that the water level maintain in the boiler is 50% of the drum level.The PID controller was tuned by Ziegler-Nichlos Method there by the gain is obtained.
K_p=Proportional Gain=0.0063
K_i=Integral Gain=0.00002739
K_d= Derivative Gain=0.36225

The closed loop response of the SISO system of level control in the boiler in fig.7 was obtain from simulink model for SISO system to control level in the boiler.

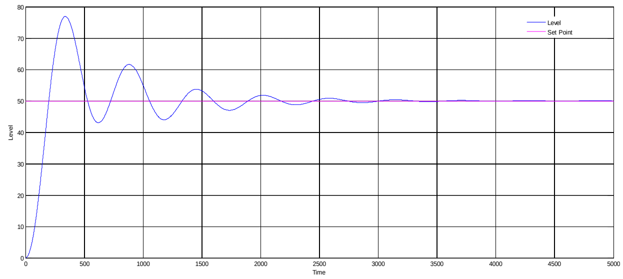

Figure 7: Closed loop response of the SISO system of Level

Due to some interactions in the system the closed response of the interacting system settling time is high and stbility also very less. To overcome this difficult we are going to Non-interacting system by decoupling the multi input multi output system to single input single output system. The settling time for interacting system of level is 32,000 ms and peak overshoot is very high. In order to maintain the stability the response of non-interacting system for level settling time is minimised to 4,000 ms in Non-interacting system.

10. Conclusions

We can conclude this paper by comparing the performance of decentralized PID and decoupled PID controller. Decoupled PID is more reliable and effective than decentralized PID. 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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