



Addis Ababa University

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

**BOILER DRUM WATER LEVEL CONTROL USING FUZZY
SLIDING MODE CONTROLLER**

A thesis submitted to Addis Ababa Institute of Technology, School of
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In partial fulfillment of the requirement for the Degree of Master of
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By: Jemila Wudu Hassen

Advisor: Dr. Dereje Shiferaw

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APPROVED BY BOARD OF EXAMINERS

_____	_____
Chairman, Department of Graduate Committee	Signature
 <u>Dr. Dereje Shiferaw</u>	_____
Name of Advisor	Signature
_____	_____
Name of External Examiner	Signature
_____	_____
Name of Internal Examiner	Signature

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Abstract

Boiling water to create steam is a crucial step in the process industries. An important part of this process boiler drum water level control. For a variety of reasons, it's crucial to keep the drum's water level at the proper level. When the water level is too high, the steam purification equipment floods, which allows water and contaminants to leak into the steam system. The effectiveness of the treatment and recirculation function is decreased by a too-low water level. It is typically challenging to control the drum water level of the boiler due to the system's significant disturbance (like steam disturbance), nonlinearity in mathematical modeling, strong coupling between input and output parameters, and multivariable features.

To overcome this problem a sliding mode controller with fuzzy logic controller (FSMC) is proposed. Also PID and SMC applied to the system in contrast. Since the drum water level controller's task is to level the boiler drum at startup point which is 10 perunit and keep it there at steady steam load. The results prove that sliding mode controller with fuzzy leads to better performance in overshoot, settling time and chattering effect elimination than PID and SMC controller. There is no overshoot in FSMC or 0 overshoot, has quick settling time which is 41.9228sec and no chattering effect. However, sliding mode controller exhibit fast rise time which is 13.1080sec than PID and FSMC which is 30.9 and 15.1947sec respectively. Also exhibit high chattering effect. This conduct is improper for a mechanical force or other physical indication. Additionally, in this work it is proven that when the amount of steam mass flow rate disturbance increase, achieving desired trajectory using PID controller decrease. But a desired trajectory can be achieved using SMC and FSMC whenever the steam mass flow rate disturbance increases. The water level control system is verified and simulated using MATLAB software.

Key word: Drum level control, sliding mode control, fuzzy sliding mode control

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LIST OF ACRONYM

Acronym	Description
PID	Proportional, Integral, Derivative
SMC	Sliding mode control
FSMC	Fuzzy sliding mode control
MIMO	Multi-input Multi-output
PWR	Pressurized water reactors
AGA	Adaptive genetic algorithm
RASMC	Robust adaptive sliding mode control
MPC	Model Predictive Control
MFs	Membership Functions

CHAPTER ONE

1 Introduction

1.1 Background of the study

A steam boiler is a closed vessel, generally made of steel, in which water is heated by some source of heat produced by combustion of fuel (mainly coal or coke) and ultimately to generate steam [1]. Chemical energy of stored fuel is converted into the heat energy and this heat energy is absorbed by the water which converts into a steam. The boiler receives water from the feed water system in order to automatically meet the demand for steam. The steam system also gathers and regulates the steam generated by the boiler. To get to the site of usage, the created steam is piped there. Generally, the heat generated causes the water that is flowing through the drum tubes to evaporate and release as steam. Throughout the system, steam pressure is controlled via valves and monitored by steam pressure gauges.

Steam has many applications in the process industries. It is used by, among other things, turbines, reactors, distillation columns, heat exchangers, and other types of process equipment. As a result, the amount of water reduces and the drum dries up if there is no water input to balance the steam that is leaving. For safe and efficient operation of boiler, water level is a very essential parameter. Too low water level, the boiler may be burnt dry, and may lead to explosion of boiler; too high water level, the separation of steam and water would be impaired, and make the pipe wall of superheater be damaged [1].

One of the common challenges/problem in boiler operation is control of steam supply continuously at high pressure and temperature. According to research published in the literature [2], poor level control of the drum water level is accountable for 30% of emergency shutdowns in pressurized water reactor (PWR) plants. Various controlling mechanism used to control the boiler system so that it works properly. The controller should maintain drum pressure and water level within acceptable ranges for all operating conditions [3]. It is important to realize that drum-type boiler is a highly nonlinear complex system and it is difficult to design an effective controller for such system with Shrink/Swell phenomena [4]. The drum level controller's objective is to level the drum upon boiler startup point and keep it there at a steady steam load [5].

1.2 Statement of the problem

Boilers have many serious injuries and destruction of property [6]. Too low water levels may cause overheating of boiler tubes and too high water levels lead to improper separation of water and steam resulting in poor efficiency. Poor level control of the drum water level, in accordance with research found in the literature [2], is the reason for 30% of emergency shutdowns in pressurized water reactor (PWR) plants. The boiler process has a number of control problems. Such as:-

- Boilers are highly nonlinear from a process dynamic point of view, and their dynamics change depending on the operating point.
- Boiler system is time varying and multi- input multi- output (MIMO). Shrink/Swell phenomenon is the main challenge in regulating such nonlinear drum water level dynamics
- The boiler process is inherently unstable due to the integrating effect of drum level. Instability in drum level, for instance, has very serious physical consequences.
- Boilers are commonly used in a situation where the load can change suddenly and without warning.

Specifically, factors affecting drum level are

- Feed water flow
- Steam flow
- Steam pressure
- Boiler pressure
- Drum temperature
- Variation of steam flow and feed water flow

As a result, stable control of water level in boiler drum is a necessary requirement for safe and efficient operation of boiler. The boiler system is controlled using a variety of techniques to ensure its maximum efficiency. Traditionally boilers have been controlled by PID controller [7]. Although the usual PID controller design is well understood, it is possible that better controller might be attained given the complexity of the Boiler Drum Water Level control problem.

In this thesis fuzzy sliding mode controller is proposed in order to overcome the above problems by Developing Mathematical modeling for a drum type boiler which can describe the boiler system briefly as a first step. Then by Designing Sliding mode controller. Finally by

optimizing Sliding Mode Controller parameters using Fuzzy Logic to overcome chattering problem in sliding mode controller.

1.3 Objective

The general objective of this thesis is to design a controller for boiler drum water level to its desired level by substituting feed water for the steam exiting the boiler which maintain a steady mass/heat balance.

The specific objectives are

- To developed Mathematical modeling for a drum type boiler
- To design a PID and Sliding mode controller and integrated with the plant model to monitor the water level.
- To design a fuzzy sliding mode controller (FSMC) to overcome chattering problem in sliding mode controller.
- To simulate PID controller, sliding mode controller and fuzzy sliding mode controller (FSMC) using MATLAB software. Then analysis and compare the two approaches.

1.4 Methodology

This thesis starts with theoretical backgrounds of non-linear dynamic boiler system behavior, its main problems and literatures about controller design to overcome the problem. After comparing various controller performances then an appropriate technique selected to solve the problems of the system. Then PID, Sliding mode and Fuzzy sliding mode controllers (FSMC) has designed to compare and contrast. Finally, the stability and accuracy of the system investigated for all controllers' analysis using 'Matlab' v.12.2 software.

1.5 Scope of the thesis

The scope of this thesis described with the following works

1. Mathematical model of drum dynamics developed
2. PID and Sliding mode controller designed and integrated with the plant model and output level is simulated on MATLAB
3. Then, Fuzzy sliding mode controller designed and integrated with the plant model and output level is simulated on MATLAB
4. Finally, the result from each controllers analyzed and compared using MATLAB software.

1.6 Outline of the thesis

The thesis layout presented on a more detailed chapter-by-chapter basis. The paper organized as follows.

In **chapter 1**, introduction, problem of statement, objective, scope and the overall working methodology of the thesis is discussed. Literatures about mathematical modeling and controller design of boiler drum water level system is discussed in the **next** chapter. **Chapter 3** gives detail descriptions of boiler system, boiler components, types and working principles in detail. In **chapter, 4-** The boiler drum of the coal-fired thermal power plant is mathematically modeled using revised versions of the mass balance and energy balance equations. Also studies and comparisons of various control techniques proposed for the designed model. So that PID, sliding mode and fuzzy sliding mode controller techniques designed. Then the proposed controllers simulated in MATLAB and their performance evaluated under different performance parameters in **chapter 5**.

Finally, **Chapter 6** summarizes the work done and results obtained. Additionally, the conclusion and suggestions for further research were provided.

CHAPTER TWO

2 LITERATURE REVIEW

This chapter reviews some of the earlier work on boiler modeling and boiler control. Sections from this chapter are organized as follows

- i. **Literature Review on Boiler Modeling**
- ii. **Literature Review on Boiler Control.**

2.1 Literature Review on Boiler Modeling

Boiler system filled with challenges caused by a number of necessary safety and control requirements, as well as financial and legal concerns. In order to research plant transient characteristics, develop and design control strategies to satisfy strict operational requirements, dynamic simulation models of industrial boilers are crucial. For many years, there has been a continuous initiative to model boilers. According to the many system modules or components, the construction of dynamic models for boiler systems is based on the laws of conservation of mass, momentum, and energy. In this thesis a non-linear boiler-turbine model developed by Bell and Astrom [16] is used. The boiler is typical 160MW oil fired, drum type boiler in Sweden [16]. A few physical parameters that describe the model's representation of the complicated dynamics of the drum, downcomer, and riser components. Among various boiler mathematical modeling, some are reviewed below.

The author [4] developed a mathematical model to describe the dynamics of a natural circulation boiler's drum-level by combining balance equations with steam volumetric ratio which is defined from the mixture of steam /water in the lower part of the drum. Step changes in heat rate and steam demand considered in simulation session. The model also accounts for the distribution of steam in the riser tubes and drum, the shrink/swell phenomenon, and the energy transfer between the working fluid and the metallic boiler walls.

As many of other literatures, [13] describes the drum water level as a state in the model presented by simple fourth order nonlinear model for a natural circulation drum boiler system . The researcher discuss better design of water level give rise to the chance of designing better level controllers. The model is based on first principle and characterized by a few physical parameters. Those parameters obtained from steam table and construction data. Additionally, the major dynamical behavior of the process captured in the model. To model forced circulation boiler, little changes are required. "The models have been validated against experimental data."

This paper considered shrink and swell phenomenon in a better way so that more accurate water level obtained in more detail.

Consequently, additional equation required. These equations also derived from first principles. Since the model explain the boiler in detail and it is of fourth order, it is quite complex. Complex mathematical models makes controller designs difficult.it is the main drawback of the model.

The research in [9] outline a methodology of developing a mathematical modeling of an industrial boiler using multiple ordinary differential and algebraic equations guided by the bond graph. Bond graph approach was used to analyze the temperature dynamics of the boiler's subsystems, including the economizer, steam drum, super heater, and desuperheater. The model tested using industrial Boiler performance test data. The model derived above dealt only with the water/steam cycles, in which they absorb heat from high temperature flue gas or combustion product. So that the flue gas or combustion dynamic model should be considered. The absence of a dynamic mathematical model that describes the flue gas or combustion model is the main limitation of the model.

2.2 Literature Review on Boiler Control

The objective of the boiler drum level control systems is to maintain the water/steam interface at its optimal setting in order to guarantee a steady flow of steam. The mass-heat balance is obtained by replacing the steam leaving the boiler with feedwater. The water/steam drum experiences a number of perturbations that disturb the interface level. Due to the complex dynamics of shrink and swell phenomena, controlling the drum level is challenging. These result in a non-minimal phase behavior that is greatly affected by the operating circumstances. Traditionally boilers have been controlled by PI control [7]. Many literatures design controllers to solve the problem in boiler drum water level. Some of them are mentioned below.

In [2], the authors discussed about **sliding mode controller optimized with adaptive genetic algorithm** used for dealing with parameter uncertainty and strong disturbance in boiler drum and also explained about PID controller. In this paper, the sliding mode controller designed by taking the error of drum water level, its velocity and its accelerated speed into s-function. Moreover, its stability proved by using Lyapunov stability theorem. From the simulation result, the author [2], prove that the sliding mode controller with AGA has smaller overshoots, faster response and better steady-state performance than PID controller. So that, the author conclude

that sliding mode control method with AGA can adequately solve the problem of parameter uncertainty and strong disturbance also prove that it is a valid and feasible method. **H. Moradi, M. Saffar-Avval, and F. Bakhtiari-Nejad** discuss about the two control strategies used to achieve a desired tracking of drum water level. **The robust sliding mode and H-infinity control.** These controllers implemented under transient conditions and in the presence of model uncertainty. Transfer function with time varying parameters between drum water level (as output variable); feed water and steam mass rate (as input) model considered.

The author [3] compare the two controllers by some criteria's. H-infinity controller designed based on μ synthesis with DK-iteration algorithm. It guarantee robust stability and performance of the system. However, high oscillation occur for the required variation of feed water and steam mass rate. It cause a disadvantage for feed water dampers and electricity demands from a power grid. Which leads to high-energy consumption.

Sliding mode controller track its objective in short command times and with good performance. Smooth and rapid response with less oscillatory behavior of control efforts (feed water and steam mass rate) performed. Less feed water mass rate and less energy consumption required for regulation problem. Consequently, less steam mass rate lead to less consumption, which is appropriate for the electricity demand from a power grid. However, less amount of oscillation occur since there exists a discontinuity in sliding mode controller.

The author [12] Propose **robust adaptive sliding mode control (RASMC) and traditional control scheme, type I servo controller** which is designed for nonlinear multiple input multiple output (MIMO) model of industrial boiler turbine unit. Simulation results conducted to validate and demonstrate their effectiveness.

The superiority of RASMC over the type I servo controller proved regarding to performance and objective tracking. In type I servo controller, Oscillation, Weak performance and instability observed. This consequently led to unstable drum water level, which reduce the safety and reliability of the boiler turbine unit. The existence of unstable quasi-periodic solution occur during disturbance rejection and keeping the system dynamic behavior. However, RASMC can efficiently. Chattering effect or oscillation eliminated while using RASMC. So that, the variation of the drum water level is stable without jumps and oscillation.

In [20], the steam flow parameters of a boiler **optimized using fuzzy logic controller** after it is controlled using conventional **PID controller**. When using a fuzzy logic controller, better

outcomes are produced. Maximum overshoot for the fuzzy logic controller was 9.35%, whereas the traditional PID controller's was 47.3%. Settling time for PID controller and fuzzy logic controller measured as 10.14 seconds and 7.18 seconds respectively. The PID controller gives a very high overshoot and high settling time.

The principle for the design of a **sliding mod control** based on reaching law discussed by [21].reaching law include two phases. The reaching phase (which drive the system to stable manifold) and sliding phase (which drive the system slide to equilibrium). Sliding mode control implemented on a linear plant to make it work as linear plant.

An internal model control based on **neural networks** discussed by [16] targets the power stations boiler drum water level. While applying the steam flux signal to the internal model controller, it considers the effects of load variations, which has feed-forward compensation for steam flux disturbance and can prevent the occurrence of "false water level".

The issue of managing a boiler drum's performance and its NO_x emission level in the presence of changes in steam demand is the subject of **S. Minhajullah's** work. Consequently, a model that incorporates both boiler and NO_x models was enhanced. This model was created using information from the Li and Thompson NO_x emission models and the Astrom and Bell drum boiler models, respectively.

The system is controlled with a PI controller and model predictive control (MPC). As a result, the suggested controller (MPC) performs better and maintains plant stability when the demand for steam varies suddenly than PI.

Although the boiler system is nonlinear, this work considers the dynamics of the plant to be linear. Further, the author can develop non-linear boiler model including NO_x and other emission pollutants like CO and O₂.

T. R. Rangaswamy and S. P. Vijayaragavan proposed Conventional PID controller for efficient drum water level control system proposed. Conventional PID controller is simple in structure and reliable in operation performance. The performance of the boiler compared considering rise time, settling time, peak overshoot, ISE and IAE. But given the complexity of the Boiler Drum Water Level control problem it is difficult to get better performance using this controller.

CHAPTER THREE

3 BOILER SYSTEM

3.1 BOILERS IN BRIEF

The boiler system mainly consists of three systems. Fuel system, feed water system and steam system [8]. The **fuel system** includes combustion of fuel ultimately used to generate steam by some source of heat produced by combustion of fuel. The fuel type utilized in the system determines the equipment needed inside. Fuels, which commonly used in boilers, are coal, oil, and gas for producing heat. **Feed water system** give the required amount of water to the boiler. Finally the steam produced from the boiled water which is commonly called **Steam system**.

Steam produced by boilers is used in a variety of industries for heating, processing, and powering steam turbines. According to their different use, Boilers classified in a number of ways [1].

1. According to the method of heating:
 - i. *Fire Tube boiler*
 - ii. *Water Tube Boiler*
2. According to the axis of the shell:
 - i. *Horizontal boiler*
 - ii. *Inclined boilers*
 - iii. *Vertical boiler*
3. According to the method of circulation of water and steam:
 - i. *Natural circulation boilers*
 - ii. *Forced circulation boilers*
4. According to the number of tubes:
 - i. *Single tube*
 - ii. *Multi tubular*
5. According to the use
 - i. *Stationary boiler*
 - ii. *Mobile boiler*
6. According to the source of heat

- i. Fuel (solid, liquid, or gaseous)*
- ii. Electrical energy*
- iii. Nuclear energy*

Boilers are frequently categorized according to whether the gas flows inside or outside the tubes [3]. Flue gases circulate inside the tubes of fire tube boilers while the gas flows outside the tubes of water tube boilers [9]. Below is a discussion of each type's characteristics.

1. Fire Tube boiler

- A fire tube boiler is a boiler in which the water surrounds the tubes that contain the hot flue gases.
- These boilers are classified as low-pressure boilers since the steam they produce has a pressure of 20 to 25 bar. Nine tons of steam are produced each hour by these boilers. So that there is a lower likelihood of exploding.
- There is no clear way provided for the circulation of water, hence the direction of the water flow is not well defined.
- Ultimately efficiency of fire tube boilers is about 75%.
- Fire tube boilers can be utilized in small power plants but are not suited for large power plants due to their low pressure and efficiency.
- This boiler is difficult to construct

2. Water Tube Boiler

- A water tube boiler is a type of boiler in which the tubes are surrounded by hot flue gases and contain water.
- These boilers fall within the high-pressure boiler category. These boilers produce high-pressure steam. The boiler pressure can reach 100 bar, making it appropriate for big power plants. However, because of its high steam pressure, there is a larger possibility of bursting or explosion.
- The water circulation's direction is clearly defined, meaning that it has a set path to follow.
- The overall efficiency of water tube boiler with economizer is up to 90%.
- They are easy to maintain, repair and clean as they are externally fired.
- Easy to construct

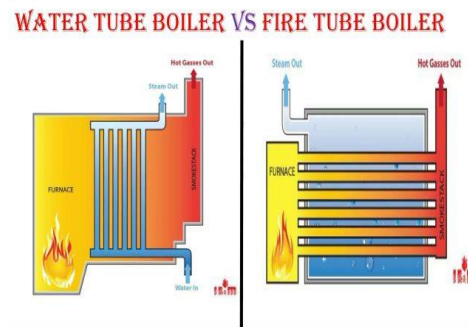


Figure 3-1 Water tube boiler diagram [9]

3.2 Main parts of boiler

Boiler components can vary, but the most common components include a firebox, burners, drums, tubes and a boiler feed water [8]. Economizer, super heater, feed pump, Water level indicator, Pressure gauge, Safety valve, Fusible plug, Steam stop valve, Blow off valve or blowdown valve, Feed check valve, Steam separator, Steam trap, Feed pump, Injector and air pre heater considered as accessories [9]. The devices attached to the boiler as accessories are in charge of improving the boiler's performance and efficiency.

Firebox

The firebox is where the system's fuel and air combine to form a fire

Burners

In order for combustion to take place, burners inject fuel and air through a distribution system that combines them at the right concentrations. Most boilers heat the boiler system with coal, natural gas, or fuel oil burners.

Drum

At the top of the water tube is a reservoir of water or steam. Drums serve as a phase separator for the steam and water mixture and keep the produced steam in the water tubes [1]. The upper drum of a boiler where the produced steam is collected is known as the **steam drum**. The lower drum in a boiler is called a **mud drum**. The steam drum is only partially full, although the mud drum and water tubes are totally filled with water. Which helps to maintain the vapor space in the upper drum and allows the saturated steam to collect and pass out to the super heater.

The mud drum's bottom collects sediment, which the blowdown process removes. Small amounts of water are removed from the boiler during this procedure to get rid of salts and suspended particulates that might collect in the steam drum. The blowdown process can be continuous (where a tiny amount of boiler water is continuously removed) or intermittent (where a valve on the bottom of the mud drum is occasionally opened).

Water Tubes:

Riser water tube

Risers are commonly defined as heat-collecting surfaces made of tubing that transport boiler-circulating water upward to the steam drum [1]. The mud drum or the water wall header at the furnace's base may be the source of the risers. Radiant energy from the fireball is largely absorbed by the boiler's circulating water when it is inside the risers jacketing the furnace.

Downcomer water tube

Through tubes known as downcomers, water is transported from the boiler drum to the mud drum or to the water wall feed water header. The downcomers are situated outside the furnace cavity and are not heated.

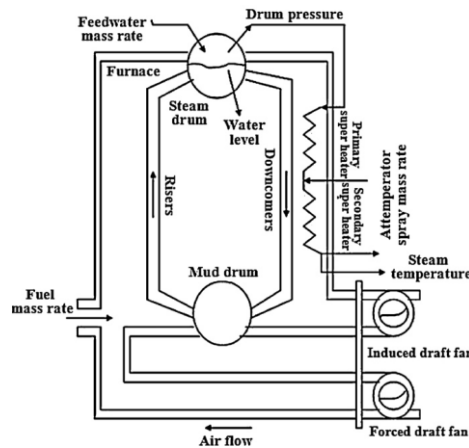


Figure 3-2 Schematic of the boiler unit performance [3]

3.3 Boiler Accessories

The devices that increase the boiler's efficiency are the accessories that are installed with it [9]. The crucial add-ons installed on the boiler are air preheater, Super heater, economizer, feed pump, water level indicator, pressure gauge, safety valve, fusible plug, steam stop valve, blow off or blow down valve, feed check valve, injector and so on are boiler accessories. Some of them are discussed below.

Super heater

Generally, boiler generates wet steam. Then by passing it through super heater, the steam temperature increased further to any desired degrees.

Economizers

Is a plant in which the feed water is preheated before it enters into a boiler, the heat required for this purpose is extracted from the waste flue gases going out of the boiler. By preheating the water, it also aids in the elimination of dissolved gases, reducing the tendency for corrosion [10]. It is placed between the furnace and entry into the chimney.

Feed Pump

The function of feed pump is to deliver water to the boiler at the pressure at which steam generation takes place.

3.4 Principles of Operation of Boilers

The water is kept in a closed container called the boiler. Thus, the fundamental idea behind a boiler is to use thermal energy to change water into steam. At first, water is supplied into the chamber or the sealed vessel of the boiler. The boiler receives water from the feed water system. Which automatically adjust the demand for steam. Water lost in the boiler is replaced through a (1) **Condensate** or condensed steam returned from the processes and (2) **Makeup water** (treated raw water) which must come from outside the plant processes [2]. The feed water to the boiler is treated to achieve the required chemical composition. Then the Hot gasses formed from the furnace meet the water vessel. After reaching a specific temperature, the water in the vessel boils as a result of the heat energy provided to the boiler [11]. Further heating of the water results in the production of steam and the observation of the transformation of water from a liquid to a gaseous state.

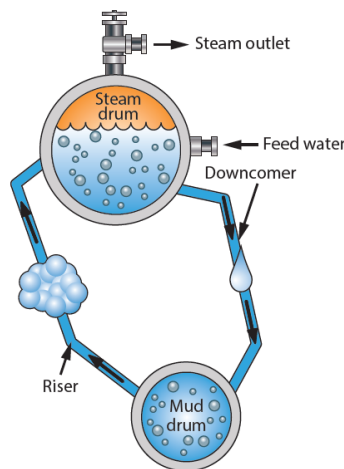


Figure 3-3 water circulation [12]

3.5 Boiler drum water level control

Water being heated to a steamy state is a crucial step in the process industries [8]. One of the core functions of this process is the control of the water level, which is accomplished by establishing a water-steam interaction in a cylindrical tank called the drum, which is typically lying on its side and is situated towards the head of the boiler. Numerous factors make it essential to keep the drum's water level. As a result of overflow caused by an excessive water level, water and contaminants are carried into the steam system and onto the steam purification equipment. The performance of the treatment and recycling function decreases when the water level is too low [13] [14]. Even tube failure can ensue from it. Due to overheating from a shortage of cooling water on the boiling surfaces, it may potentially cause tube failure. Normal drum level expectations include maintaining the level within 2 to 5 cm of the set-point while allowing for brief fluctuations in load [15]. Several factors influence how it functions. Bubbles and other steam-supporting surface products can be found just below water/steam level interface when there is boiling [16] [17]. These bubbles have volume and as a result move water about in the drum, giving a false impression of the actual water level inside. The pressure within the drum also has an impact on the level. If the drum pressure changes as a result of load demands, the steam bubbles spread or shrink in response to these pressure variations because they compress under pressure.

A larger steam demand will result in a decrease in drum pressure and an expansion of the steam bubbles, giving the impression that the water level is higher than it actually is [6]. When more water is actually needed, the feed water intake is shut down as a result of the false higher water level. Swell is the term for an increase in water level defined as a reduction in drum pressure. Shrink is the term for a drop in water level brought on by an increase in drum pressure. One of three methods of drum level control—single-element, two-element, or three-element—can be used to provide efficient water level control in a drum [18].

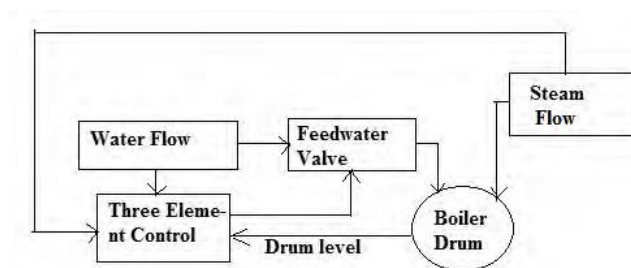


Figure 3-4 Basic elements of drum level system [8]

CHAPTER FOUR

4 Mathematical modeling and Controller design for Boiler

Drum system

4.1 Boiler drum model

As general, boiler models categorized into three groups, i.e. complex models, moderately complex models, and simpler models [19]. The non-linear boiler-turbine model used in this thesis is a common one that Bell and Astrom suggested [16]. The boiler is typical 160MW oil fired, drum type boiler in Sweden [16]. The model parameters specifications listed in Table 1.

parameter	specification
Rated Power	160MW
Drum steam Pressure	140 kg/cm ²
Super heater steam Temperature	535°C
Volume of drum	40m ³
Feed water Temperature	300°C

Table 4-1 Boiler-Turbine System parameter detail [16]

In this model, much of the system behavior captured here is by considering the mass and energy balance equations for total system. Simple physics based models for system studies is the motive of the model. So that it can be categorizes under simpler model. The model shows the complex nature of the drum, downcomer, and riser parts, each of which is characterized by a few physical characteristics. Any drum power plant can easily be reproduced by scaling it.

4.1.1 DYNAMIC BEHAVIOUR OF A BOILER DRUM LEVEL

A third-order nonlinear model (Bell and Astrom, 1987) [22] has been used to represent the dynamics of a 160 MW oil-fired drum-type FFPU (fossil fuel power unit) for overall wide-range simulations. The valve actuators' positions, which control the mass flow rates of fuel (u_1 in pu), steam to the turbine (u_2 in pu), and feed water to the drum (u_3 in pu), are the inputs. Drum water level variation (L in m), electric power (E in MW), and drum steam pressure (P in kg/cm) are the three outputs [22]. Interaction-related problems are usually present when

BOILER DRUM WATER LEVEL CONTROL USING FUZZY SLIDING MODE CONTROLLER

designing multi-loop control systems for MIMO processes. A multi-loop system is broken down into a number of equivalent single loops for design in order to overcome the problems. So that, feed water (water flow) is directly related to drum water level and steam flow considered as disturbance.

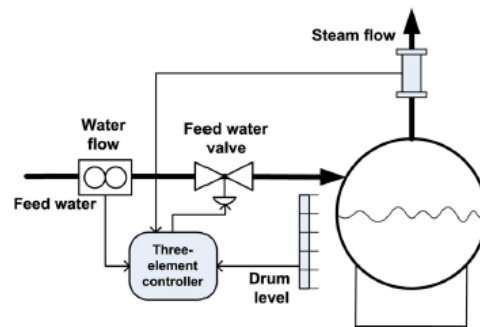


Figure 4-1 Boiler water level control [6]

Astrom and Bell claim that by taking into account the mass and energy balance equations for the entire system, the effects of the water flow and steam flow can be analytically recorded [17]. According to Astrom and Bell, the following figure illustrates the fundamental design of a boiler.

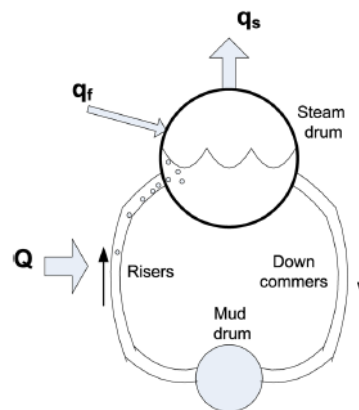


Figure 4-2 Schematic diagram of Boiler drum [21]

$$\rho = \frac{m}{v}, \quad m = \rho * v \quad \text{where } \rho = \text{density}, \quad m = \text{mass}, \quad v = \text{volume} \quad \text{Eq 4-1}$$

Take time derivative

$$\frac{d\rho}{dt} = \left(\frac{dm}{dt}\right)/v \quad \text{Eq 4-2}$$

Conservation of mass

$$\frac{dm}{dt} = \frac{\dot{m}_{in} - \dot{m}_{out}}{v} \quad Eq\ 4-3$$

Where: ρ_s Steam Density, ρ_w Water Density, q_s Steam flow rate, q_f feed water flow rate, qr flow momentum in riser tube, V_t Total drum volume, V_{wt} Total water volume, h_s Specific enthalpy of steam, h_w Specific enthalpy of water, C_p Metal specific heat capacity, m Mass, V_{st} Total steam volume, T temperature.

Energy balance

For any system, the energy going into the system must equal the energy coming out of the system plus any accumulation of energy in the system.

Rate of change of energy of steam & water in the drum = total energy of steam & water mixture after leaving the water walls + energy of drum water - energy of drum steam

$$\begin{aligned} \frac{d}{dt} [\rho_s h_s V_{st} + \rho_w h_w V_{wt} + m c_p T] \\ = \rho + q_{fw} h_{fw} - q_s h_s \end{aligned} \quad Eq\ 4-4$$

Since internal energy is $u_s = h_s - \frac{\rho}{\rho_s}$ and $u_w = h_w - \frac{\rho}{\rho_w}$

Where $V_t = V_{st} + V_{wt}$

Total Steam Volume

$$V_{st} = V_{drum} - V_w + a_m V_r \quad Eq\ 4-5$$

Total Water Volume

$$V_{wt} = V_w + V_{dc} + (1 - a_m) V_r \quad Eq\ 4-6$$

Mass Balance

For any system, the total mass going into the system must equal the total mass coming out of the system plus any accumulation of mass in the system.

Rate of change of mass of steam & water in the drum = feed water flow to the drum – steam flow from the drum

$$\frac{d}{dt} [\rho_s V_{st} + \rho_w V_{wt}] = q_{fw} - q_s \quad Eq\ 4-7$$

$\rho_s V_{st} = m_{st}$ and $\rho_w V_{wt} = m_{wt}$ which is derived from Eq 3-1

Eliminate dV_{wt}/dt between (3.4) and (3.7)

$$\begin{aligned} h_c \frac{d}{dt} (\rho_s V_{st}) + \left[\rho_s V_{st} \frac{dh_s}{dt} + \rho_w V_{wt} \frac{dh_w}{dt} + mc_p \frac{dT}{dt} \right] & \quad Eq\ 4-8 \\ = P - q_{fw}(h_w - h_{fw}) - q_s h_c & \\ h_c \frac{d}{dt} (\rho_s V_{st}) + \left[\rho_s V_{st} \frac{dh_s}{dt} + \rho_w V_{wt} \frac{dh_w}{dt} + mc_p \frac{dT}{dt} \right] & \\ = P - q_{fw}(h_w - h_{fw}) - q_s h_c & \end{aligned}$$

Rewritten as

$$\begin{aligned} e_{11} \frac{dp}{dt} = P - q_{fw}(h_w - h_{fw}) - q_s h_c & \quad Eq\ 4-9 \\ e_{11} = h_c V_{st} \frac{d\rho_s}{dp} + \rho_s V_{st} \frac{dh_s}{dp} + \rho_w V_{wt} \frac{dh_w}{dp} + mc_p \frac{dT_s}{dp} & \end{aligned}$$

Total condensation flow

$$q_c = \frac{1}{h_c} \left[\rho_s V_{st} \frac{dh_s}{dt} + \rho_w V_{wt} \frac{dh_w}{dt} + mc_p \frac{dT_s}{dt} \right] \quad Eq\ 4-10$$

Mass Balance for Riser Section

$$\frac{d}{dt} (\rho_s a_m V_r) + \frac{d}{dt} (\rho_w (1 - a_m) V_r) = q_{dc} - q_r \quad Eq\ 4-11$$

$$\begin{aligned} \frac{d}{dt} (\rho_s h_s a_m V_r) + \frac{d}{dt} (\rho_w h_w (1 - a_m) V_r) & \\ = P + q_{dc} h_w - x_r q_r h_s - (1 - x_r) q_r h_w & \quad Eq\ 4-12 \\ = P + q_{dc} h_w - x_r q_r h_c - q_r h_w & \end{aligned}$$

Eliminate q_r , between (3.11) and (3.12)

$$\begin{aligned} \frac{d}{dt} (\rho_s h_s a_m V_r) - (h_w + x_r h_c) \frac{d}{dt} (\rho_s a_m V_r) & \\ + \frac{d}{dt} (\rho_w h_w (1 - a_m) V_r) - (h_w + x_r h_c) & \quad Eq\ 4-13 \\ \frac{d}{dt} (\rho_w (1 - a_m) V_r) = P - x_r h_c q_{dc} & \end{aligned}$$

Simplify to

$$\begin{aligned} h_c (1 - x_r) \frac{d}{dt} (\rho_s a_m V_r) + \rho_w (1 - a_m) V_r \frac{dh_w}{dt} & \\ - x_r h_c \frac{d}{dt} (\rho_w (1 - a_m) V_r) + \rho_s a_m V_r \frac{dh_s}{dt} & \quad Eq\ 4-14 \\ = P - x_r h_c q_{dc} & \end{aligned}$$

Drum Level

Average steam-water volume ratio

$$x = \frac{\rho_s a}{\rho_s a + \rho_w (1 - x)}$$

Solving with respect to a

$$a = a(x) = \frac{\rho_w x}{\rho_s + (\rho_w - \rho_s)x}$$

Assume

$$x(\xi) = x_r \xi \quad 0 \leq \xi \leq 1 \quad \text{Eq 4-15}$$

Hence

$$\begin{aligned} a_m &= \int_0^1 a(x_r \xi) d\xi = \frac{1}{x_r} \int_0^1 a(x_r \xi) d(x_r \xi) \\ &= \frac{1}{x_r} \int_0^{x_r} a(x) dx \\ &= \frac{\rho_w}{\rho_w - \rho_s} \left[1 - \frac{\rho_s}{(\rho_w - \rho_s)x_r} \ln \left(1 + \frac{\rho_w - \rho_s}{\rho_s} x_r \right) \right] \\ \ell &= \frac{V_w + a_m V_r}{A} \end{aligned} \quad \text{Eq 4-16}$$

Downcomer Flow

Momentum balance

$$a_m V_r (\rho_w - \rho_s) = \frac{1}{2} k q_{dc}^2 \quad \text{Eq 4-17}$$

Riser flow from (B)

$$q_r = q_{dc} - \frac{d}{dt} (\rho_s a_m V_r) - \frac{d}{dt} (\rho_w (1 - a_m) V_r) \quad \text{Eq 4-18}$$

Summary

$$\begin{aligned} &\frac{d}{dt} [\rho_s h_s V_{st} + \rho_w h_w V_{wt} + m c_p T] \\ &= P + q_{fw} h_{fw} - q_s h_s \quad (\text{from Eq 3.4}) \\ &\frac{d}{dt} [\rho_s V_{st} + \rho_w V_{wt}] = q_{fw} - q_s \quad (\text{from Eq 3.7}) \\ &h_c (1 - x_r) \frac{d}{dt} (\rho_s a_m V_r) + \rho_w (1 - a_m) V_r \frac{dh_w}{dt} \\ &- x h_c \frac{d}{dt} (\rho_w (1 - a_m) V_r) + \rho_s a_m V_r \frac{dh_s}{dt} \quad (\text{from Eq 3.14}) \\ &= P - x_r h_c q_{dc} \end{aligned}$$

The state variables drum pressure p , water volume in drum V_w and average steam quality at riser outlet x_r are chosen as the state variables. Then the state equations can be written as

$$\begin{cases} e_{11} \frac{dp}{dt} + e_{12} \frac{dV_w}{dt} + e_{13} \frac{dx_r}{dt} = P + q_{fw}h_{fw} - q_s h_s \\ e_{21} \frac{dp}{dt} + e_{22} \frac{dV_w}{dt} + e_{23} \frac{dx_r}{dt} = q_{fw} - q_s \\ e_{31} \frac{dp}{dt} + e_{33} \frac{dx_r}{dt} = P - q_{dc}x_r h_c \end{cases} \quad Eq\ 4-19$$

$$e_{11} = \left(\frac{d\rho_s}{dp} h_s + \rho_s \frac{dh_s}{dp} \right) V_{st} + \left(\frac{d\rho_w}{dp} h_w + \rho_w \frac{dh_w}{dp} \right) V_{wt} + mc_p \frac{dT_s}{dp}$$

$$e_{12} = \rho_w h_w - \rho_s h_s$$

$$e_{13} = (\rho_s h_s - \rho_w h_w) V_r$$

$$e_{21} = \frac{d\rho_s}{dp} V_{st} + \frac{d\rho_w}{dp} V_{wt}$$

$$e_{22} = \rho_w - \rho_s$$

$$e_{23} = (\rho_s - \rho_w) V_r \frac{da_m}{dx_r}$$

$$\begin{aligned} e_{31} &= \left[(1 - x_r) h_c \frac{h\rho_s}{dp} + \rho_s \frac{dh_s}{dp} \right] a_m V_r \\ &+ \left[\rho_w \frac{dh_w}{dp} - x_r h_c \frac{d\rho_w}{dp} \right] (1 - a_m) V_r \\ e_{33} &= [(1 - x_r)\rho_s + x_r\rho_w] h_c V_r \frac{da_m}{dx_r} \end{aligned} \quad Eq\ 4-20$$

The transfer function model can be obtained from linear statespace model using the Laplace transform [22]. The process of modeling is omitted since the scope of the thesis is limited to show the process.

Therefore, dynamic mathematical model of boiler drum water level under the action of water supply flow can be expressed as follows. In this model, the feed-water rate (u_1) is control inputs, the drum water level (h) is the output and steam mass rate (u_2) is disturbance variable represented by the transfer functions $G(s)$ and $G_{SH}(s)$. Generally, for our system, the water flow and steam flow transfer functions are,

$$G(s) = \frac{U_1}{h} = \frac{\lambda}{(s+\lambda)} \frac{\alpha_1}{s(1+\tau_1 s)} \quad Eq\ 4-21$$

$$G_{SH}(s) = \frac{U_2}{h} = \frac{\beta}{1+\tau_2 s} - \frac{\alpha_2}{s} \quad Eq\ 4-22$$

Where τ_1 and τ_2 denote time constants; α_1 , α_2 and β are the constant gains. It is impossible for traditional control approaches like PID controller to provide strong stability and performance of the uncertain time varying systems. As a result, the development of three control mechanisms is discussed next.

4.2 Controller design for Boiler Drum system

The goal of automatic control of boiler water level is to control water supply flow and keep balance with the evaporation flow. Moreover, it maintain the change of drum water level in the permitted range.

It is Obvious that the disturbances which causes drum water level changes are mainly steam flow (known as external disturbance)and water supply flow(known as internal disturbance).

4.3 Design of PID controller strategy

PID control is an important and most commonly used distributed control system. In process control today, more than 95% of the control loops are of PID type, most loops are actually PI control [23].

The transfer function of the PID controller looks as follows:

$$kp + \frac{ki}{s} + kds$$

Where

kp = Proportional gain

ki = Integral gain

kd = Derivative gain

Effects of each of controllers kp , ki and kd on a closed-loop system are summarized in the Table 4-1 below.

Close loop response	Rise time	overshoot	Settling time	Steady state error
kp	Decrease	Increase	Small change	Decrease
ki	Decrease	Increase	Increase	Eliminate
kd	Small change	Decrease	Decrease	Small change

Table 4-2 PID controller characteristics parameters [23]

4.3.1 PID tuning

The adjustment of control parameters kp , ki , and kd to the optimum values for the desired control response is called PID tuning. There are various methods for loop tuning. This include:-

- I. Manual tuning
- II. Ziegler - Nichols tuning
- III. PID tuning software

4.4 Design of sliding mode controller strategy

The sliding mode methodology is simple approach to robust control in which the nth-order problem is replaced by an equivalent first-order system [24].The application of SMC is very wide due to its simplicity, robustness and disturbance rejection capacity. A nonlinear plant can use this controller to operate as if it were slightly linear.

The design of sliding mode control law consists of the

1. Design of a suitable sliding surface as the dynamics of the system limit the sliding manifold produces a desired behavior, and
2. The development of a discontinuous control law that compels the system trajectory to encounter and maintain the sliding surface in a finite amount of time

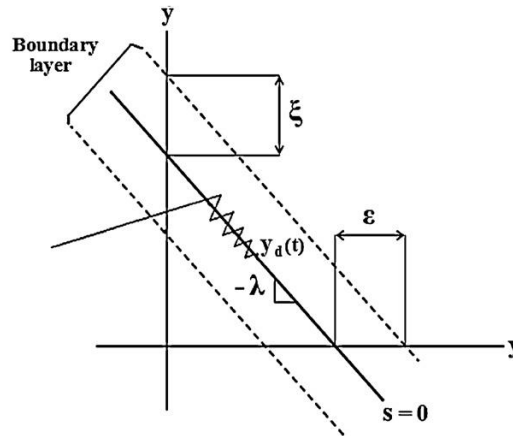


Figure 4-3 Characteristics of the sliding surface [21]

The control problem consists of developing the functions $u_i^+(x, t)$, $u_i^-(x, t)$ and the sliding surface $s(x) = 0$ so that the closed loop system shows a sliding mode on the sliding manifold $s(x) = 0$.

The transfer functions between feedwater and drum water level can be gotten as Eq. (3.21) and Eq. (3.22). Since the Bell and Astrom model is utilized as it is a genuine plant of boiler-turbine system between numerous nonlinear plant models. For overall wide-range simulations, the model represents a 160 MW oil-fired drum-type boiler-turbine generator and is characterized by the following third-order MIMO nonlinear state equation (Bell and Astrom). [17].

The sliding mode controller design for the plant model with transfer function $G(s)$ is described in this section.

Consider the nonlinear dynamic system with a single-input plant as:

$$\dot{x}(t) = f(x) + b(x)u + d(x) \dots \dots \dots \text{Eq 4-23}$$

Where, $f(x)$ & $b(x)$ are known parameters comes from eq. (3.21) and eq. (3.22) but estimated as $\hat{f}(x)$ and $d(t)$ is disturbance:

Control gain b is varied between two extreme limits as $0 < b_{min} < b < b_{max}$.

The estimation error on \hat{f} is assumed to be bounded by some known function $\gamma(x,t)$ such that

$$|f - \hat{f}| \leq \gamma \dots \dots \dots \text{Eq 4-24}$$

Therefore, the states equations used in this paper are

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = x_3$$

$$\dot{x}_3 = f(x) + b(x)u + d(x)$$

State space : $x_1 = h$

$$\dot{x}_1 = x_2 = \dot{h}$$

$$\dot{x}_2 = x_3 = \ddot{h}$$

$$\dot{x}_3 = f(x) + b(x)u + d(x) = \dddot{h}$$

4.5 Sliding mode controller design

In order $h(t)$ to track $h_d(t)$, sliding surface s is defined as

$$s(y; t) = \left(\frac{d}{dt} + \lambda \right)^{n-1} e(t) \quad \dots\dots\dots Eq \ 4-25$$

Since $n = 3$, which gives $\rightarrow s(t) = e_3(t) + Ae_2(t) + Be_1(t)$

$$e_1(t) = e(t)$$

$$e_2(t) = \dot{e}(t)$$

$$e_3(t) = \ddot{e}(t)$$

$$= \ddot{e}(t) + A \dot{e}(t) + Be(t)$$

A and B represents the slope of the sliding surface are chosen to undertake $e(t)$ to be convergent. In order to keep $e(t)$ Convergent, all the roots of the characteristic equation should have negative real part. So that the ranges of A and B are $A > 0$ and $B > 0$

$$e(t) = h_d(t) - h(t) \quad \dots\dots\dots Eq \ 4-26$$

Where $e(t)$ is the tracking error and h_d is the ideal position

$$\dot{e}_1 = \dot{e} = \dot{h}_d - \dot{h}$$

$$\dot{e}_2 = \ddot{e} = \ddot{h}_d - \ddot{h}$$

$$\dot{e}_3 = \dddot{e} = \dddot{h}_d - \dddot{h}$$

Then,
$$\dot{s} = \dot{e}_3 + A\dot{e}_2 + B\dot{e}_1 \dots\dots\dots Eq \ 4-27$$

From Eq 4.3

$$\dot{s} = (hd - f(x) - b(x)u - d(x)) + Ae_{2+} + Be_1 \dots \dots \text{Eq 4-28}$$

Use the Lyapunov function: $V = \frac{1}{2}s^2$ in order to keep the system to be stable

Then we get: $\dot{V} = s\dot{s}(t)$

$$\begin{aligned} &= s(\dot{e}_3 + Ae_{2+} + Be_1) \\ &= s(hd - f(x) - b(x)u - d(x)) + Ae_{2+} + Be_1 \end{aligned}$$

From Eq. (4.1) & (4.6), SMC may be designed as:

$$u(t) = \frac{1}{b(x)}(hd - f(x) - b(x)u - d(x) + Ae_3(t) + Be_2(t) \dots \dots \text{Eq 4-29}$$

$$\dot{V}(s) = s(-f(x) - d(t) - [d_{\max} + |f(x)| \operatorname{sgn}(s)])$$

$$= |s|(-d(t) - d_{\max}) \operatorname{sgn}(s) + |s|(-f(x) - f(x)) \operatorname{sgn}(s) < 0$$

A simplified form of u can be written as:

$$u(t) = \frac{1}{b(x)}(-f(x, t) + Ae_3(t) + Be_2(t) - \eta \operatorname{sgn}(s)) \dots \dots \text{Eq 4-30}$$

η is a positive real number and sgn is the signum function

4.6 Fuzzy logic controller strategy

To apply fuzzy logic technique to a real application requires the following three steps [25]:

1. **Fuzzification** – the conversion of traditional, crisp data into fuzzy data or membership functions (MFs)
2. **Fuzzy Inference Process** – To get the fuzzy output, combine the membership functions with the control rules.
3. **Defuzzification** – use different technique to calculate each related output and put them into a table, which is the lookup table. During an application, use the output from the lookup table in accordance with the current input.

BOILER DRUM WATER LEVEL CONTROL USING FUZZY SLIDING MODE CONTROLLER

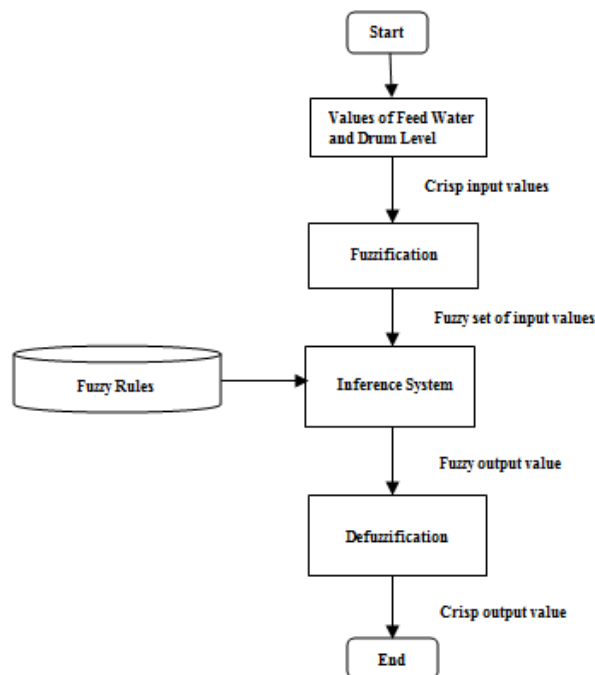


Figure 4-4 Architecture of fuzzy controller [25]

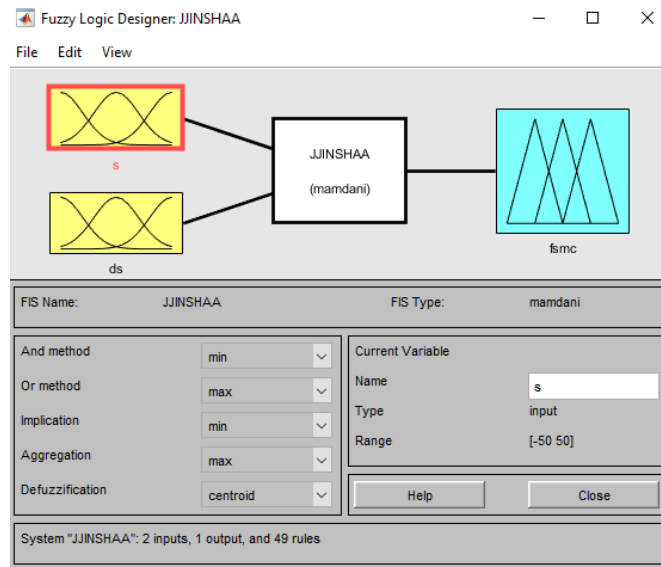


Figure 4-5 Fuzzy logic input output system

4.7 Fuzzy sliding mode controller design

There is chattering in the control output as a result of the discontinuous control component in the SMC control law. The Fuzzy Logic Controller's smooth control action feature is employed to prevent SMC from chattering and create a (FSMC) Fuzzy Sliding Mode Controller [26].

BOILER DRUM WATER LEVEL CONTROL USING FUZZY SLIDING MODE CONTROLLER

This approach can handle the SMC chattering issue well.

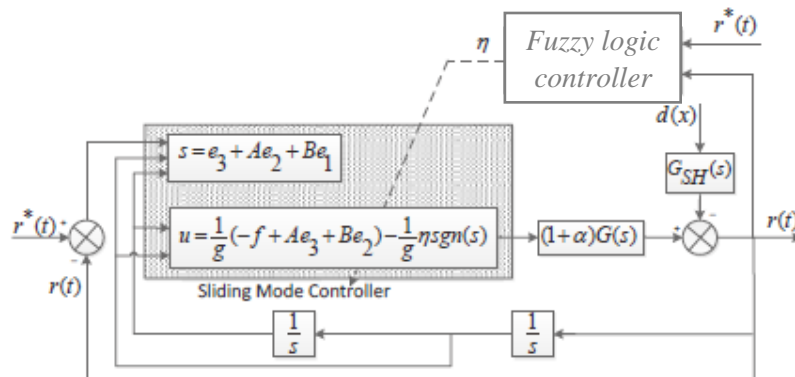


Figure 4-6 Structure of Fuzzy sliding mode controller [21]

Instead of the function Sgn(S), a fuzzy system of the Mamdani type is utilized in the control law of the SMC. The sliding function and its derivative are used as inputs, and the system produces the variable FSMC, which ranges from -50 to +50. There are various methods used in the hybrid system of sliding mode control and fuzzy logic control system. Summary of various methods used in the hybrid FSMC is described below the table.

No.	Input	Fuzzy Rules	Output
1	$\begin{Bmatrix} e \\ \dot{e} \end{Bmatrix}$	\longrightarrow	k
2	$\begin{Bmatrix} e \\ \dot{e} \\ \int e \end{Bmatrix}$	\longrightarrow	k
3	$\begin{Bmatrix} s \\ \Delta s \end{Bmatrix}$	\longrightarrow	u
4	$\begin{Bmatrix} e \\ \Delta e \end{Bmatrix}$	\longrightarrow	$ksat(s)$
5	s	\longrightarrow	k
6	$s\dot{s}$	\longrightarrow	Δk
7	$ s $	\longrightarrow	k

Table 4-3 Summary of various methods used in the hybrid FSMC [24]

The boiler drum water level in the drum will be managed by the fuzzy controller. The water flow is the result. These rules eliminate error when there is a higher level of error and the system is unstable. The system is more stable when the amount of mistake is low. And depending on whether the rate of change of error is positive or negative, the flow of water is either increased or decreased. In the fuzzy toolbox, rules are created for this as shown in table

BOILER DRUM WATER LEVEL CONTROL USING FUZZY SLIDING MODE CONTROLLER

4-2. Rules stands for NB, NM, NS, Z, PS, PM, PB are (negative big, negative medium, negative small, zero, positive small, positive medium, positive big) respectively.

$s(t)/$ $\Delta s(t)$	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	Z
NM	NB	NM	NM	NM	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PS	PM	PB
PM	NS	Z	PS	PM	PM	PM	PB
PB	Z	PS	PS	PM	PB	PB	PB

Table 4-4 Rule base for fuzzy logic controller [27]

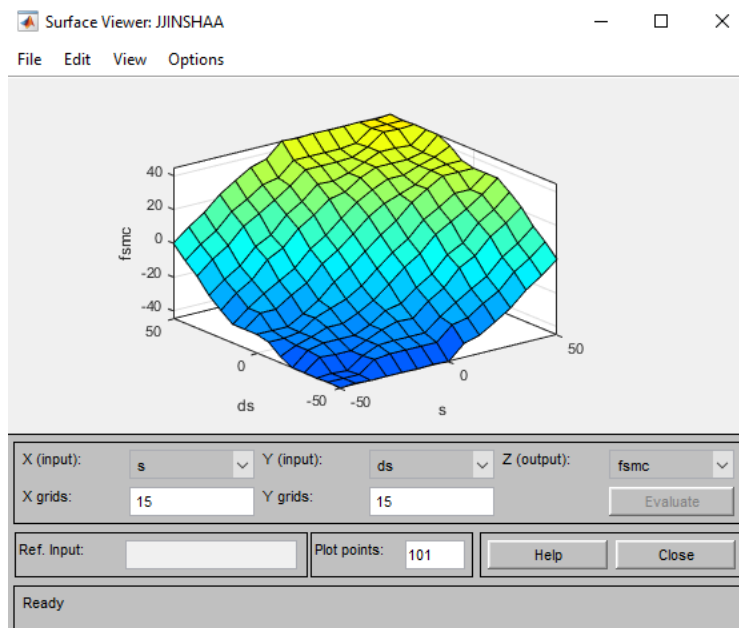


Figure 4-7 Fuzzy rule surface

CHAPTER FIVE

5 Simulation result and discussion

5.1 Introduction

A control system is made up of subsystems and plants (processes) placed together to get a specific output with a specific performance from a specific input. Open loop and closed loop are the two main configurations of control systems. The open loop and close loop design of boiler drum water level will be discussed in this chapter.

On the Matlab/Simulink library, models are created for the three main circumstances of getting level outputs. A model of a plant without a controller that produces an open loop response for the boiler drum's nonlinear dynamics has been developed. The secondly plant model is simulated with a PID and SMC controllers. Finally, FSMC is developed that improves the problem in PID and SMC.

In this simulation, PID, SMC and FSMC compared. The aims of this simulation is to know the performance of each controller and which controller is more robust while Change of steam mass rate is considered as disturbance.

5.2 Boiler drum model

Mathematical modeling of the drum dynamics is designed on MATLAB/SIMULINK environment as shown in Fig. 5.1. Below.

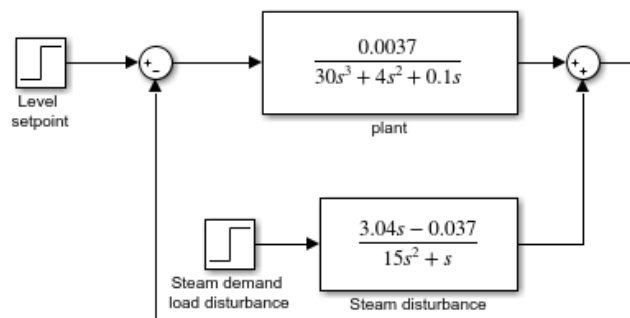


Figure 5-1 Block diagram of Boiler Drum model

5.3 Simulation result and analysis

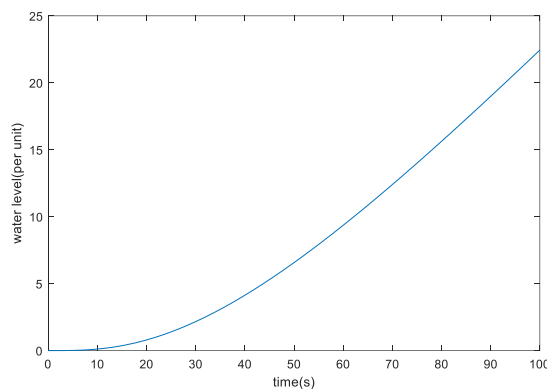
In this paper, a step change in water level is given to the system. The system is operating at the point with water level of $H = 10$ per unit and the control goal is to stabilize the drum level to 10 per unit.

The simulation results are shown in Figures 5.2-5.15.

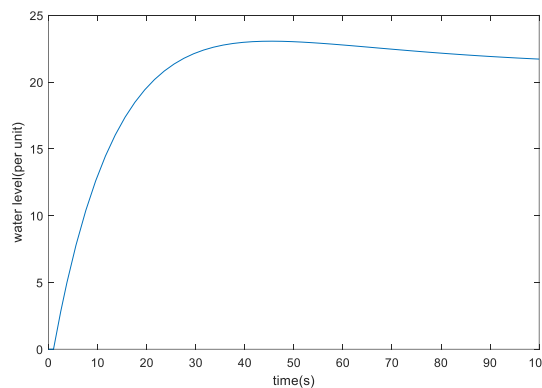
5.3.1 Open loop response with disturbance and without disturbance

The overall open loop plant model without disturbance and with disturbance respectively is simulated in MATLAB Simulink environment shown in figs below.

The water level is considered as an output in $G(s)$, feedwater flow is input to the system whereas a change in the steam mass rate is regarded as a system disturbance. Given that the output of heated steam is constant, any changes brought on by load fluctuations are considered system disturbances.



(A)



(B)

Figure 5-2 Step response of open loop model (A) without disturbance, (B) with disturbance

Fig 5-2(A) shows the step response of the water level for an open loop model. Whereas Fig 5-2 (B) shows the step response of the system with 10 p.u steam load demand disturbance.

5.3.2 Close loop response with disturbance and without disturbance

In order to keep the level at the required position, we must add some amount of water for every amount of steam that leaves the drum. 10 per unit of water needed to be added because in our investigation 10 per unit of steam was evaporating; this was accomplished as illustrated in the figure below.

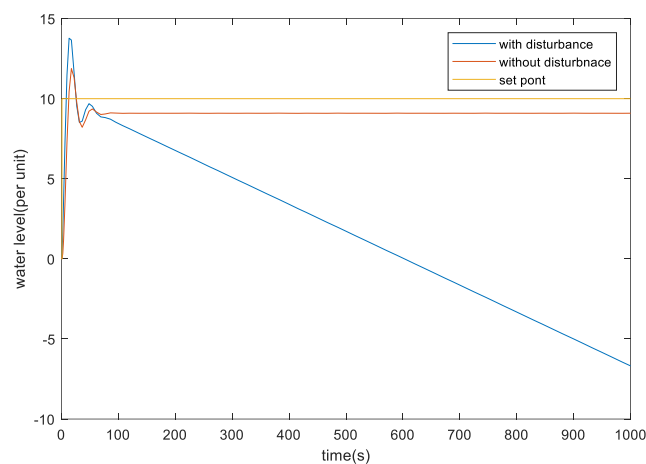


Figure 5-3 step response of close loop model with disturbance and without disturbance

The figure 5-3 shows the close loop response of the model with disturbance and without disturbance. As a result, the plant model without disturbance has small overshoot and close to the set point than the plant model with disturbance. Whereas, the plant model with disturbance has large overshoot.

5.4 Close loop response of the plant with PID, sliding mode and fuzzy sliding mode controller

5.4.1 PID controller result analysis

In order to verify the results of Fuzzy sliding mode control method, PID and SMC is designed about the above-established mathematic model of the boiler drum water level. The simulation results are as follows: In this paper the PID controller is designed using automatic PID tuning tool in Matlab.

BOILER DRUM WATER LEVEL CONTROL USING FUZZY SLIDING MODE CONTROLLER

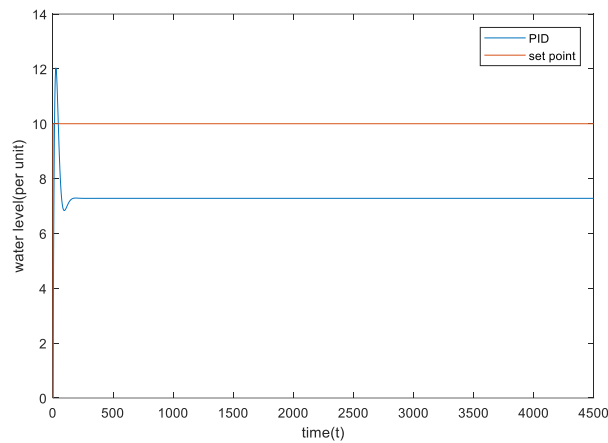


Figure 5-4 Time response of drum water level in tracking of desired trajectory for a step input with disturbance; for PID controller

As shown in Fig 5-4, the PID control system overshoot is very large also rises and settles slowly. Moreover, it cannot achieve the desired trajectory due to its less steam mass flow rate disturbance handling capacity.

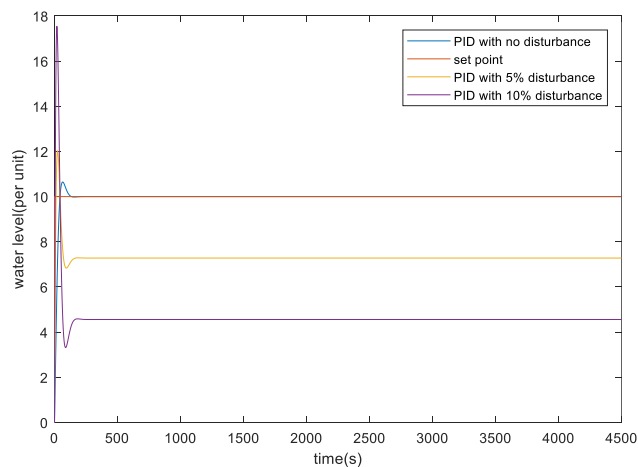


Figure 5-5 Time response of drum water level in tracking of desired trajectory for a step input; for PID controller

As shown in figure 5-5, the performance of PID control system is tested by increasing the amount of steam disturbance in the system. However, when disturbance increase the system overshoot gets very large also the ability to achieve its trajectory decrease.

5.4.2 Sliding mode controller result analysis

The effect of SMC is tested in Matlab environment. The parameters in Eq. (3-21), Eq. (3-22) and parameters in sliding mode controller are presented in Table 5-1. These values are put into

BOILER DRUM WATER LEVEL CONTROL USING FUZZY SLIDING MODE CONTROLLER

the given system in the required equations. The control objective is to maintain the water level constant at desired level h_d or 10 p.u.

λ	0.1	β	3.6	η	1~100
α_1	0.037	α_2	0.037	A	60
τ_1	30	τ_2	15	B	80

Table 5-1 Real nominal values for the parameters of $G(s)$ and $G_{SH}(s)$ [28]

According to the description of boiler drum, we construct the overall sliding function which is described below.

Plant: from Eq. (1) \dot{x}_3 is calculated as

$$\dot{x}_3 = -\left(\frac{1+\lambda\tau_1}{\tau_1}\right)x_3 - \frac{\lambda}{\tau_1}x_2 + \frac{\lambda\alpha_1}{\tau_1}u$$

$$\text{Where: } f(x) = -\left(\frac{1+\lambda\tau_1}{\tau_1}\right)x_3 - \frac{\lambda}{\tau_1}x_2, \quad b(x) = \frac{\lambda\alpha_1}{\tau_1}$$

$$\dot{x}_3 = 0.000123u - 0.122x_3 - 0.0033x_2$$

Sliding function: $s(t) = e_3(t) + Ae_2(t) + Be_1(t)$

Controller: $u(t) = \frac{1}{b(x)}(-f(x, t) + Ae_3(t) + Be_2(t) - \eta \operatorname{sgn}(s))$

Tracking error: $e(t) = h_d(t) - h(t)$

$$\dot{e}_1 = \dot{e} = \dot{h}_d - \dot{h}$$

$$\dot{e}_2 = \ddot{e} = \ddot{h}_d - \ddot{h}$$

$$\dot{e}_3 = \dddot{e} = \dddot{h}_d - \dddot{h}$$

State space variables: $x_1 = h$

$$\dot{x}_1 = x_2 = \dot{h}$$

$$\dot{x}_2 = x_3 = \ddot{h}$$

$$\dot{x}_3 = f(x) + b(x)u + d(x) = \dddot{h}$$

Using the above sliding mode equations and parameters, the Simulink model is performed in MATLAB/ Simulink environment. First, design suitable sliding (switching) surface so that the

dynamics of the system confined to the sliding manifold. After switching surface design, the next important issue of sliding mode control is guaranteeing the existence of a sliding mode. The figure below shows the sliding surface of SMC.

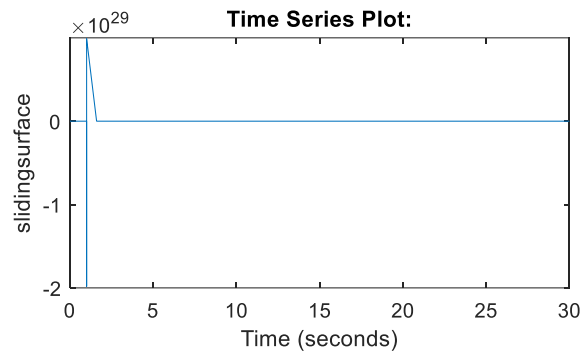


Figure 5-6 stable sliding surface

Figure 5-6 shows the system trajectories stay on the surface once they are there. However there exists a high overshoot before it takes a sliding surface. The dynamics of the system depends on A & B which represents the slope of the sliding surface. A low value of A & B leads to slower error convergence and longer tracking time, whereas a high value of A & B leads to faster convergence and lesser tracking time. But if the value of A & B is too high, it can cause an overshoot in the system states. Here, the value of A & B is 60&80 respectively. Less tracking time exhibit however a high overshoot occur.

The equivalent control forces the error variables to move towards zero immediately. As a result, the desired behavior can be achieved after the sliding mode starts.

Displaying the plant's controlled input, which is actually the controller's output. This control input displays the controller parameter's operating range. A control law u is selected to confirm the sliding condition. However, the control law must be discontinuous over S in order to account for the occurrence of disturbances (t). This results in chattering (see figure 5.7). This conduct is improper for a mechanical force or other physical indication.

BOILER DRUM WATER LEVEL CONTROL USING FUZZY SLIDING MODE CONTROLLER

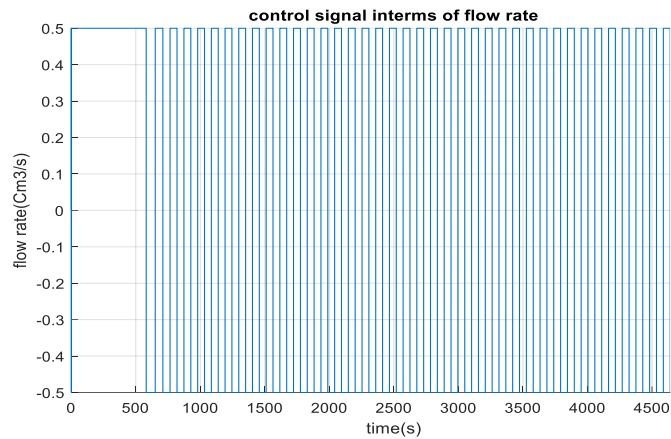


Figure 5-7 control signal in terms of flow rate

As shown in Figure 5.8, when the step response curve is rising, the sliding mode controller performs effectively and reliably, rising faster than the FSMC and reaching the steady state faster. The result is that the uncertain plants respond more appropriately when using a sliding mode controller to monitor any intended target (especially for shorter time intervals of commands). The suggested control strategies can be easily applied to various dynamic systems (with different transfer functions), it should be noted.

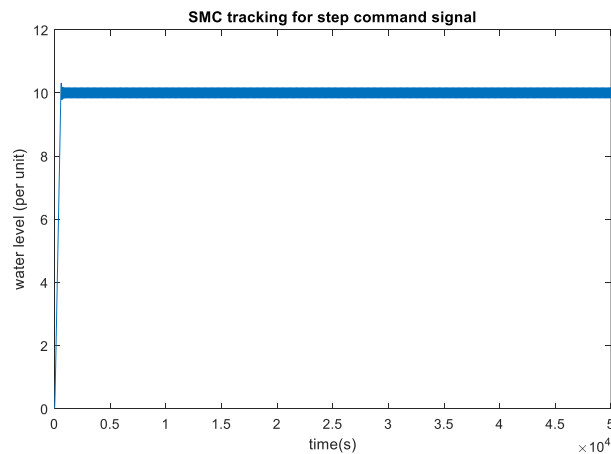


Figure 5-8 Time response of drum water level in tracking of desired trajectory for a step input; for sliding mode controller

BOILER DRUM WATER LEVEL CONTROL USING FUZZY SLIDING MODE CONTROLLER

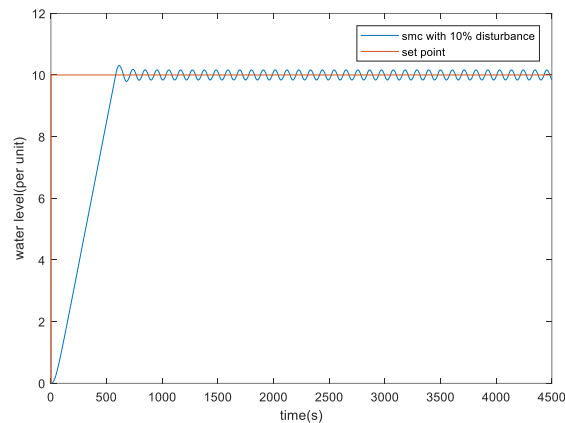


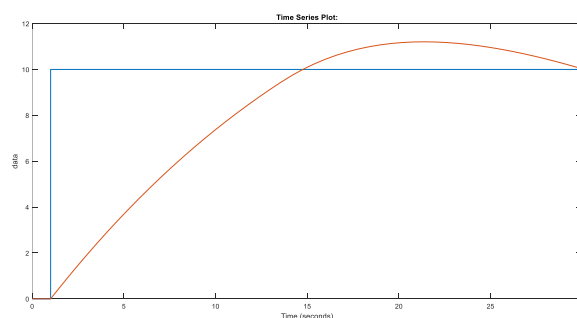
Figure 5-9 Time response of drum water level in tracking of desired trajectory for a step input with an increase in 10% disturbance; for sliding mode controller

There is no significant change observed while the steam mass flow rate disturbance is increased to 10%. SMC can still achieve its desired trajectory of 10pu. However, there still exists a chattering effect.

Parameter Tuning

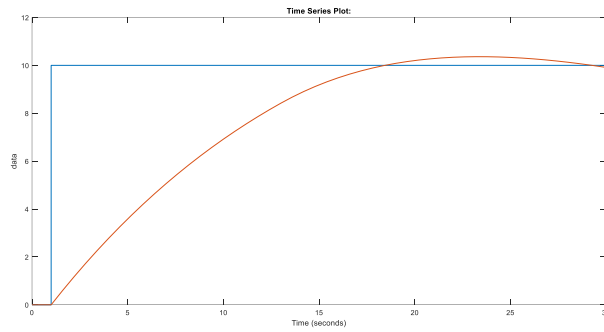
The effect of each parameter variation discussed graphically. But, this is too difficult due to the complexity of mathematics and nonlinear systems. There are three parameters to tune in total: A and B to construct s-surface, η to construct V_{fw} .

Effect of η



(A)

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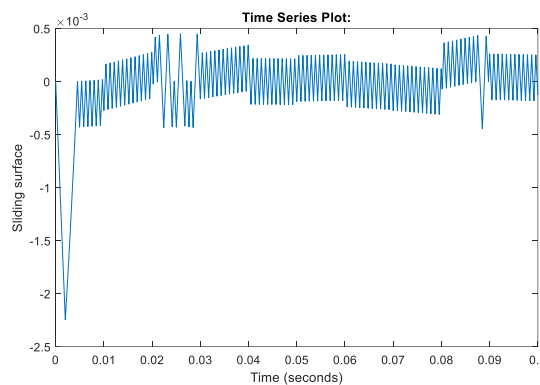


(B)

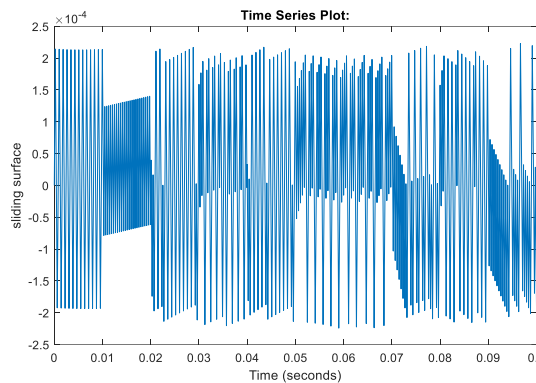
Figure 5-10 Response of water level using sliding mode controller when (A) $\eta = 100$ (B) $\eta = 0.01$

The more decreasing the rate of the Lyapunov function from $\dot{V} \leq -\eta|s|$ as larger the value of η . Figure 5-10 demonstrates the comparison. $\eta = 100$ in Figure 5-10 (A), whereas $\eta = 0.01$ in Figure 5-10 (B). Other parameters are set identically. It is obvious that the responses with large η are faster, regardless of the type of controls.

Effect of A and B



(A)



(B)

Figure 5-11 Response of sliding surface using sliding surface when (A) $B = 8, A=60$ (B) $A=600, B=800$

The function of SMC is to force $s = 0$ first. Then, the property of $s = 0$ will force $e = 0$ when t approaches infinity. Since $s(t) = e_3(t) + Ae_2(t) + Be_1(t)$, implying that e converges exponentially with time constant. Too small value of A and B will cause the system to converge sluggishly. Although, too large value of A and B may destabilize the system, or have the system converged sluggishly. A proper choice of A and B would stabilize the system.

Generally, fast dynamic response, insensitivity to changes in plant parameters, and resistance to outside disturbance are some of its appealing properties. However, one issue that restricts the use of the sliding mode controller is chattering.

5.4.3 Fuzzy sliding mode controller simulation analysis

For evaluating the optimal tuning FSMC effectiveness, this section gives the simulation experiment under different scenarios.

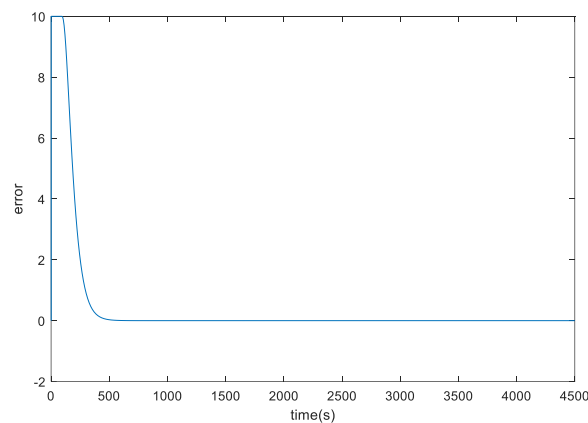


Figure 5-12 Errors of drum water level in tracking of desired trajectory for step input; for fuzzy sliding mode controller

Fig 5-12 shows the error of fuzzy sliding mode controller and how fuzzy rules eliminate error. The system is more stable when the amount of error is low [29]. Additionally, depending on whether the rate of change of error is positive or negative, the flow of water is either increased or decreased. To ensure system stability and essentially get rid of the chattering issue, the switching gain constant in the sliding mode controller is adjusted using the fuzzy logic controller.

BOILER DRUM WATER LEVEL CONTROL USING FUZZY SLIDING MODE CONTROLLER

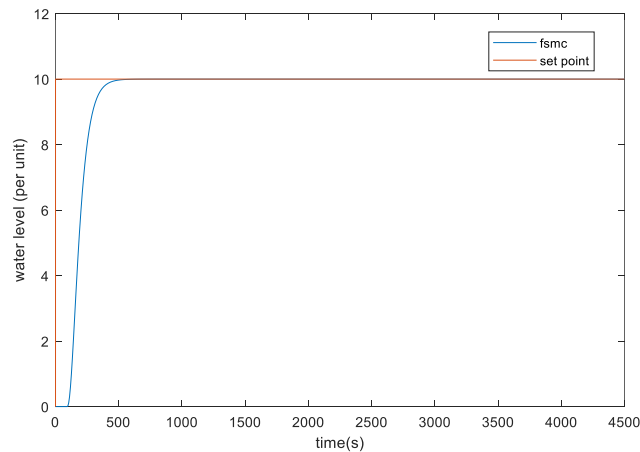


Figure 5-13 Time response of drum water level in tracking of desired trajectory for a step input; for a Fuzzy sliding mode controller

Fig 5-13 shows the performance of FSMC while achieving the set point or the desired trajectory of 10p.u. here in FSMC the chattering effect of the control signal which is the input to the plant problem is resolved. Additionally, there is no overshoot in FSMC.

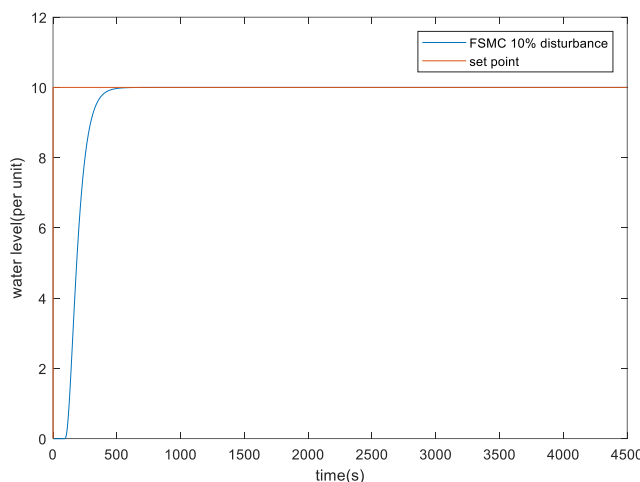


Figure 5-14 Time response of drum water level in tracking of desired trajectory for a step input of 10% an increase in steam disturbance; for a Fuzzy sliding mode controller

As figure 5-14 demonstrates, the ability to overcome an increase in steam mass flow rate disturbance is achieved in FSMC. Whenever disturbance increase, the ability to achieve its desired trajectory without any chattering effect is occupied.

BOILER DRUM WATER LEVEL CONTROL USING FUZZY SLIDING MODE CONTROLLER

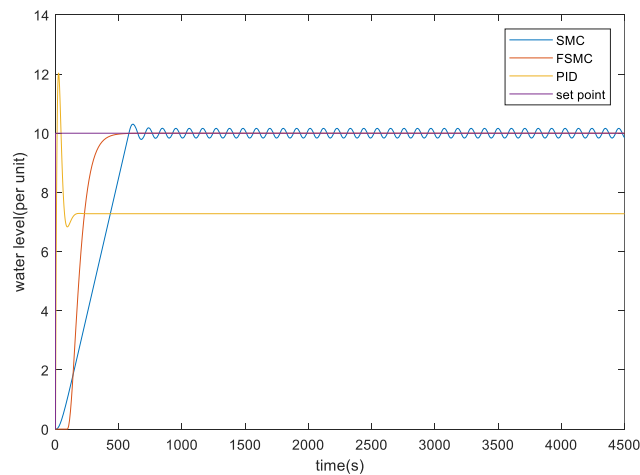


Figure 5-15 Response of system using PID, sliding mode controller and fuzzy sliding mode controller

The system is stable after 41.9228 seconds when the water level is set to 10 per unit while using FSMC, according to the graph in fig 5-15. According to the system step input simulation curve, fuzzy sliding mode control has a number of benefits over PID and SMC control, including settling time and overshoot, which can essentially meet the demand of the boiler drum water level. Whereas SMC has small rise time than PID and FSMC.

The desired trajectory of the water level in the drum in response to a step input is seen in Fig.5.15. It is shown that FSMC control outperforms than PID and SMC in tracking the desired trajectory without chattering. However, both SMC and FSMC controllers can achieve its desired trajectory while disturbance occurs but not PID controller did.

5.5 Discussion

The feed water pressure drop in the beginning led to an increase in water level. The steam mass fraction and submerged steam bubbles cause oscillation in the water level. Due to this steam disturbance, controller's performance is evaluated.

Figures and tables above with the controller replies for each show how the performance of the system with controllers has been built. The drum level overshoots significantly 6.47% for PID controller and relatively low 4.52% for SMC controller, respectively. Meanwhile, PID controller performance decreased while disturbance increased. When steam mass flow rate disturbance increased, the overshoot increased and the ability to achieve its desired trajectory decreased. As a conclusion PID disturbance handling property is low.

The performance parameters of a system using fuzzy sliding mode controller have zero overshoot, small settling time with no chattering effect when compared to PID and SMC controller. However SMC show fast rise time which is 13.1080 sec than both PID and FSMC. Both controllers can achieve their desired trajectory but SMC exhibit chattering effect. The water level response has high chattering effect for SM controllers and, which can lead to the boiler being shut off. Furthermore, the inaccuracy is significant when there is no controller. The result of fuzzy sliding mode controller is acceptable

CHAPTER SIX

6 Conclusion and recommendation

6.1 Conclusion

This study propose a hybrid controller FSMC and compare with traditional PID controller and SMC. It is designed sliding mode controller technique based on fuzzy logic for nonlinear control systems. As a result, nonlinear system stability challenges become crucial. Here, the sliding surface is created using error dynamics and a reference trajectory. This is a reliable control method, and the creation of a FSMC lessens the downsides of the sliding mode controller. On a sliding surface, this propels the state trajectory in the stable form. Real-world systems are highly complicated in nature, poorly modeled, and the classical methods are quite laborious to provide the system's desired stable performances. The intelligence heuristic method was used to create this novel hybrid controller. The suggested method is more compatible for extremely unstable systems, such as aerospace systems, this newly created controller will be more efficient.

The dynamic model of boiler water level developed in this study accounts shrink/swell phenomenon. It is more thorough and useful because it takes into account the "false water level" phenomena that is brought on by a change in the drum steam pressure when a steam flow disruption exists. The proposed controllers (SMC & FSMC) efficiency is tested using some performance parameters as discussed below the table.

PERFORMANCE PARAMETER	PID	SMC	FSMC
rise time (sec)	30.9	13.1080	15.1947
Settling time (sec)	103	53.1711	41.9228
Overshoot (%)	6.47	3.2851	0
Undershoot (%)	-	0	0
Peak (sec)	1.06	10.3069	10.0002
peak time (sec)	-	37	114

Table 6-1 performance parameter of boiler drum water level system

As seen in table 6-1 , the response of a system is observed utilizing fuzzy sliding mode control, which has excellent control over overshoot and settling time, rise time, and minimizes performance indices.

6.2 Recommendation

In this thesis, a third order non-linear MIMO boiler drum modeling is used. There is an interaction between inputs and outputs. To reduce the complication of Interaction-related problems a multi-loop system is used that is a broken down into a number of equivalent single loops. For the future work, the model should include Interaction between inputs and outputs (MIMO) system in a better way. Since designing boiler drum give rise to the chance of designing better level controllers.

While using FSMC, expert pre-definition of the sliding surface coefficients is required in sliding mode controller before the fuzzification process .In this paper trial and error method is used to determine sliding surface coefficients and fuzzy gain. For further work, other methods should be considered to obtain this parameters which leads to a better result.

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APPENDIX

Appendix A: Nomenclature

A1: Physical units

Symbol	Unit	Description
A	m^2	Area
C_p	J/kg K	Metal specific heat capacity
h	J/kg	Specific enthalpy
k_v	kg/hr	Valve sizing coefficient
m	kg	Mass
P	bar	Pressure
Q	W	Heat flow rate
T_{sat}	°C	Saturation temperature
V	m^3	Volume
V_o	m^3	Volume in hypothetical situation
T_d	s	Residence time of steam in drum
ρ_s	kg/m^3	Steam Density
ρ_w	kg/m^3	Water Density
q_s	kg/s	Steam flow rate
q_f	kg/s	feed water flow rate
q_r	kg/s	flow momentum in riser tube
V_{sd}	m^3	Steam bubble volume
V_t	m^3	Total drum volume
V_{wt}	m^3	Total water volume
h_s	J/kg	Specific enthalpy of steam
h_w	J/kg	Specific enthalpy of water
h_c	J/kg	Specific enthalpy of condensation

A2: Dimension less units

Symbol	Description
d	Drum
f_w	Feed-water
dc	Down-comer

BOILER DRUM WATER LEVEL CONTROL USING FUZZY SLIDING MODE CONTROLLER

Appendix D: Detailed simulink representaion of the system.

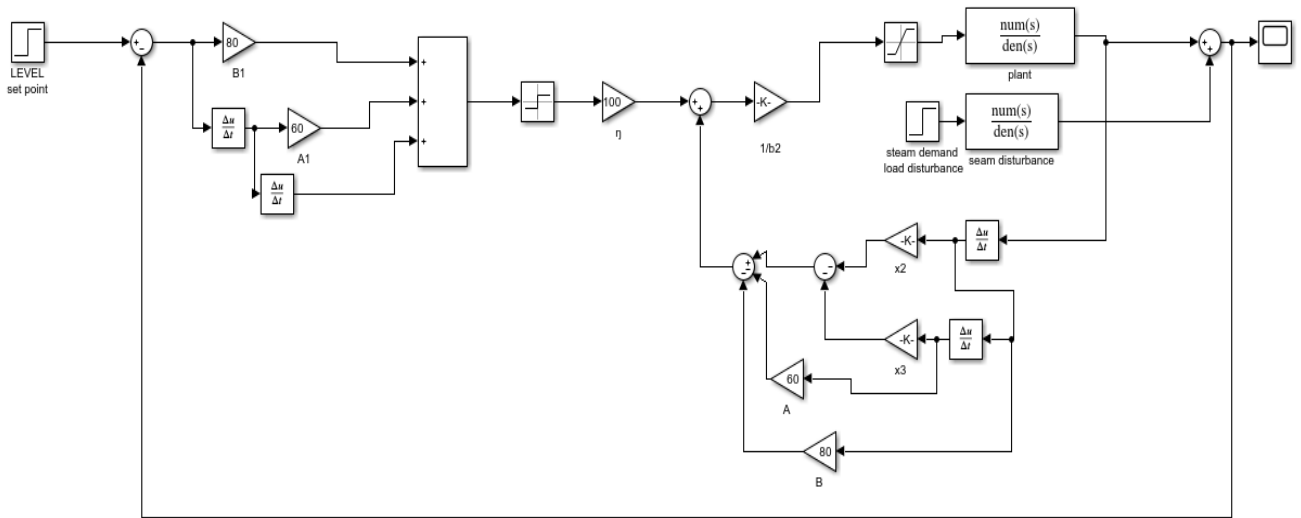


Figure 0-1 Sliding mode controller simulink model

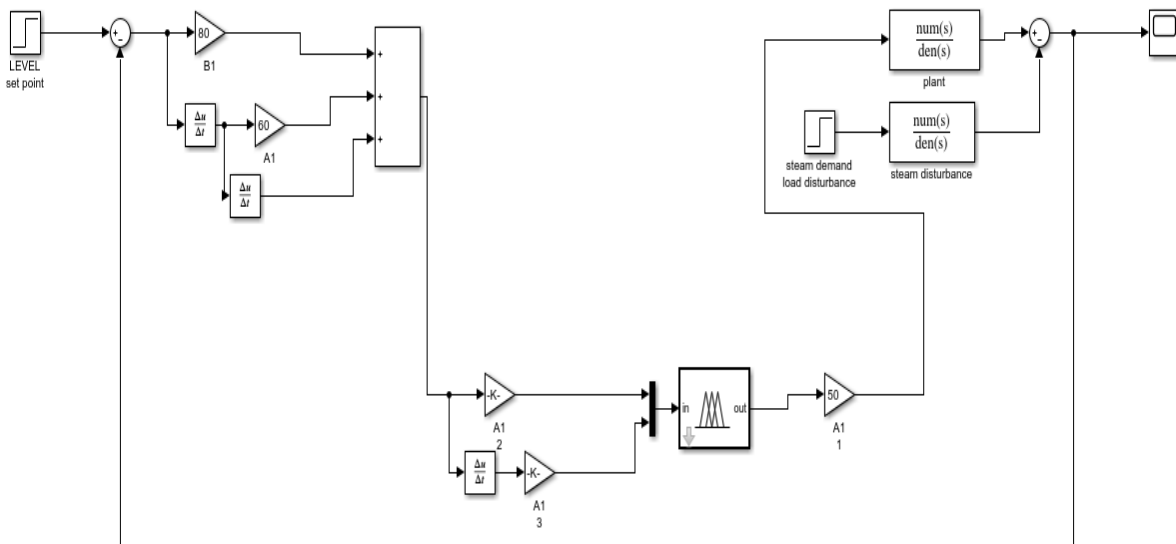


Figure 0-2 Fuzzy sliding mode controller simulink model

