Level Control of a Steam Drum using Double Feedback Loop Control Strategy along with Set point Filter

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DECLARATION

I hereby certify that the work which is presented in dissertation entitled, **"Level Control of a Steam Drum using Double Feedback Loop Control Strategy along with Set point Filter"** in partial fulfillment of the requirements for the award of degree of **Master of Engineering in Electronics Instrumentation and Control**, submitted to Electrical & Instrumentation Engineering Department of Thapar University, Patiala is an authentic record of my own work carried under the supervision of **Dr. Vikram Chopra**. It refers others researcher's work which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

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NOMENCLATURE

PID	Proportional Integral Derivative
IMC	Internal Model Control
t_r	Rise Time
t_s	Settling Time
M_p	Percentage Overshoot
ISE	Integral of Square Error
ITAE	Integral of Time Absolute Error
P	Proportional
PI	Proportional Integral
GA	Genetic Algorithm
LQR	Linear Quadratic Regulator
MFAC	Model Free Adaptive Control
FLC	Fuzzy Logic Controller
k_p	Proportional Gain
k_i	Integral Gain
k_d	Derivative Gain
k_{cr}	Ultimate Gain
P_{cr}	Ultimate Period
τ_i	Integral Time
τ_d	Derivative Time
τ_f	Filter Time Constant

ABSTRACT

Regulating the level of liquid in a boiler steam drum is of prime concern. The boiler is so manufactured that the drum level must be in the specified range. According to the demand of steam in process industries, steam drum provides steam of definite quality. The shrink and swell effect results in false level of water that leads to the measurement of three parameters including water level of drum, flow of feed water and flow of steam.

This work deals with the level control of steam drum using double feedback loop method along with set point filter. In double feedback loop method, the inner loop consists of a proportional controller and is tuned with the help of Ziegler Nichols (ZN) method while the outer loop consists of a proportional integral derivative (PID) controller and is tuned by internal model control (IMC). The internal loop is employed for attaining the process stability while the external loop helps in fine tracking of set point. Also a comparative analysis between different control schemes such as conventional PID controller, single loop IMC based PID controller and double feedback loop method is done in respect of distinct time domain performance specifications such as rise time (t_r), settling time (t_s), percentage overshoot (M_p), integral of square error (ISE) and integral of time absolute error (ITAE).

The simulation results show that the single loop IMC based PID controller is more efficient than conventional PID controller as there is an improvisation in rise time and settling time. Furthermore, the double feedback loop method shows better performance than both conventional PID controller and single loop IMC based PID controller in respect of percentage overshoot (M_p), settling time (t_s), ISE and ITAE.

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Boiler is a device that is employed to create steam by applying heat energy to water. A boiler or steam generator is a closed vessel and is employed as a cause of steam generation. There are various types of boilers that produce steam by exchanging heat from one fluid to another and this generated steam is used for different processes in various heating applications.

Steam drum is an essential part of a boiler. Water level is one of the essential parameters that must be controlled and evaluated in power plants. For the secure boiler operation, it is necessary to preserve a constant value of water level in the steam drum. The main aim of drum level controller is to bring the drum level at the desired value and maintain the level at constant steam load. If the level of water is too low, the boiler tubes get overheated and destroyed and if it is too high, the interface level between steam and water get influenced which results in the transfer of water and impurities into the steam system. Thus, there must be an optimal interface level between steam and water within the steam drum. The shrink-swell phenomenon takes place due to the variations in drum pressure that results in the change of water density in steam drum. The liquid inside the steam drum consists of bubbles because of the boiling water. As the steam demand rises, it will result in a severe rise in the level of steam drum because of increased quantity of the steam bubbles. This increase in the volume of bubbles is due to the drop in pressure in the steam drum. This phenomenon is called as ‘swell effect’. If the demand of the steam decreases the steam bubbles get collapsed and there is a reduction in the volume of bubbles due to the increased pressure of steam drum. This results in the low level of steam drum and the phenomenon is called as ‘shrink effect’. Thus the cause of shrink-swell phenomenon is the variations in the drum pressure due to which expanding and collapsing of steam bubbles take place resulting in the rising and decreasing of the drum level due to change of load [1].

There are three types of boiler drum level control [2]:

1. Single element drum level control
2. Two element drum level control

3. Three element drum level control

Single element system is the simplest approach. This method is used to measure the level. It is employed to regulate the flow of feed-water in order to maintain the level. This is the only effective method for the smaller boiler processes that possess slow and moderate load changes. The disadvantage of this approach is that level of steam drum is affected by uncontrolled feed water and steam disturbances

In **Two element system,** the steam flow is considered as the feed-forward element to the controller output. This strategy consists of two variables that are to be controlled including steam flow and drum level. This system is a combination of feed-forward and feedback system. The drawback of this approach is that this method is not beneficial for the pressure or load disturbances in feed-water system.

In **Three element system,** flow rate of feed-water is the third variable that is added to influence the feed-water control valve. This control strategy can handle feed-water disturbances and loads that exhibit wide rates of change despite of boiler capacity [2].

1.2 OBJECTIVE AND SCOPE OF THE DISSERTATION

The objectives of this dissertation are as follows:

- Tuning of PID controller for inverse plus integral (steam drum) process using internal model control (IMC) method in a double feedback loop for the level control of a steam drum.
- Study of basic set point filter concept and use this idea for the reduction of undesired overshoot.
- Comparative analysis of the double feedback loop method with the conventional PID controller and single loop IMC based PID controller in terms of different time domain performance specifications such as rise time (t_r), settling time (t_s), percentage overshoot (M_p) etc.

1.3 ORGANIZATION OF THE DISSERTATION

After giving a brief introduction about the topic, the dissertation is arranged as follows:

CHAPTER 2 provides a relevant literature survey regarding distinct control techniques employed for the level control of steam drum

CHAPTER 3 gives an overview of different control techniques that are used to regulate the steam drum level

CHAPTER 4 gives the problem formulation

CHAPTER 5 shows the simulation results and discussions

CHAPTER 6 provides the conclusion of entire work done and proposes the future scope.

CHAPTER 2

LITERATURE REVIEW

The literature involves number of papers reporting the regulation of water level of steam drum using different control schemes. Some of them are as follows:

Ziegler *et al.* [3] proposed two classical methods for deciding PI/PID controller parameters. The first method was designed on the basis of step response of the open loop system, which is specified by two variables. These two unknown variables were decided from a process step response and used to evaluate the controller parameters. The second method was designed on the basis of process frequency response. The gain margin (GM) and phase crossover frequency were used to determine the parameters of PID controller. The ultimate gain and ultimate period are used to evaluate the parameters of PID controller.

Mcdonald *et al.* [4] developed an optimal linear regulator theory for the development and study of multivariable control strategies which identifies the inability of the model imperfection. This method proposes an “integral type” action that assures zero steady state errors.

Rivera *et al.* [5] proposed general method of IMC with PID structure. In this paper, the parameters of PID controller can be obtained by approaching the simple feedback structure of an IMC controller. The control design depends on prior model of the process and a low pass filter is added for the robust behavior.

Nomura *et al.* [6] developed an adaptive optimal control method for temperature control of boiler steam of a thermal power plant. Also a model of coal-fired thermal power plant and automatic plant control (APC) was developed that are assumed to be one controlled unit in such a way that when adaptive optimal control system fails, APC continue to control power plant.

Cheres *et al.* [7] represented the dynamics for low order boiler model. The author presented the data and control techniques for both low and high order models of boiler. For the evaluation of data, methods and field tests are also obtained and introduced uncertainty in parameter. The errors due to inaccurate measurements are simplified and applied method for the evaluation of data is also presented.

Hogg *et al.* [8] described a predictive control strategy to control steam pressure in industrial applications. Firstly, PI controllers are used to control the steam pressure but these controllers do not work well for the variations in system parameters. A good control can be attained with the use of generalized predictive control and it has been shown that the overshoot and rise time get improved.

Huang *et al.* [9] developed a dynamic model of fire tube shell boiler by using a model based strategy. Dimeo *et al.* [10] designed a Genetic Algorithm control strategy for boiler turbine plant. In this paper, Genetic Algorithm design was coupled with PI controller and state feedback controller and then compares the results with standard linear quadratic regulator control system. It has been found that GA/PI control system shows good set point tracking capability but oscillations were introduced due to the integral action. The GA/LQR control scheme performed well but posseses finite steady state error.

Vanlandingham *et al.* [11] designed a fuzzy logic control technique for the steam drum level control. Katebi *et al.* [12] presented a comparative study for the robustness of multivariable systems using different PID tuning methods for the application of industrial boilers. Kothare *et al.* [13] proposed a model predictive control algorithm to overcome the plant limitations including non minimum phase plant characteristics, actuator constraints on flow rate of feed water, non linear dynamics of plant to achieve a better control action.

Tan *et al.* [14] proposed a multi loop PI control using H_∞ loop shaping techniques. Both the control schemes are evaluated in time plus frequency domain. It has been found that the proposed controllers show better performance in comparison with the existing multi loop controllers.

Wang *et al.* [15] developed a hybrid fuzzy control scheme to supervise the water level processes and temperature of steam of the power plant boiler. Fu *et al.* [16] designed robust PI controllers for a benchmark boiler system and better performance and robustness can be achieved with the designed PI controllers in comparison to manually tuned decentralized PI controller.

Xu *et al.* [17] proposed a cascade model predictive control strategy for drum level control. The internal loop consists of an adaptive model based controller while generalized predictive controller is used as an outer loop controller that rejects the effect of measured and unmeasured disturbances.

ZHuo *et al.* [18] proposed a design of feed forward PID control to regulate drum water level. The proposed scheme provides an effective control for the problem of “false water level”. Huang *et al.* [19] proposed an adaptive control scheme to control the level of boiler drum. The plant parameters are identified using least squares method and then the controller parameters are manipulated by Genetic algorithm control strategy.

Sundarasekaran *et al.* [20] presented a temperature-pressure compensation strategy for the better control of boiler drum level. The proposed method is much more effective for high pressure boilers. Chen *et al.* [21] proposed a self-adaptable fuzzy-PID control scheme to regulate the water level of boiler drum. It has been found that the performance of proposed method is superior to the conventional PID controller.

Isa *et al.* [22] presented three modes of PID controller for the control of automatic water level system. The response of three modes i.e. proportional, proportional-integral and proportional-integral-derivative has been measured to determine rise time, percentage overshoot, time constant and peak time.

Vijayan *et al.* [23] designed a first order set point filter to minimize the undesirable percentage overshoot to an acceptable limit. Iacob *et al.* [24] developed a control system for the boiler drum using three element cascade control to reduce shrink/swell effect. The output response of three element and single element drum level control are compared and it has been found that the three element drum level control gives the better response.

Zhou *et al.* [25] presented a comparative analysis of new immune PID controller with that of conventional PID controller to control the water level of steam drum. It has been shown that the new immune PID controller has faster response and smaller percentage overshoot than the conventional PID controller. Also the proposed method has effectively minimized the fluctuation range of level of steam drum.

Wang *et al.* [1] proposed a model free adaptive control strategy (MFAC) to regulate the superheated pressure of steam. In this paper, a comparative analysis between traditional PID and

MFAC is made and it has been found that MFAC strategy is far better than traditional PID controller.

Liu *et al.* [26] developed a three impulse cascade control system for the control of water level of steam drum. A fuzzy PID controller is used as an outer loop controller and conventional PID controller is used as an inner loop controller for the cascade control system. It has been shown that the interference caused by water flow and steam flow changes has been eliminated with the use of proposed method.

Vijayan *et al.* [27] designed a set point filter along with PID controller in double feedback loops for single input single output systems. The proposed method helped in attaining the process stability and improved performance. The outer feedback loop is used for the tracking of set-point and the internal loop is employed to attain the process stability. The external loop controller is tuned by internal model controller (IMC) method and the inner loop controller is tuned by Ziegler Nichols method. Also a set point filter is used for minimizing the undesired percentage overshoot.

Yuan *et al.* [28] developed a three impulse cascade control methodology to overcome the multi disturbance characteristics of boiler drum water level system. Bhowmik *et al.* [29] designed a three element boiler drum level control system to deal with the phenomenon of “false water level”.

Zhang *et al.* [30] developed a fuzzy self-tuning PID level controller for drum level control. The proposed method is compared with conventional three element PID control and it has been shown that the present method has smaller overshoot, shorter regulating time and stronger robustness than conventional methods.

Begum *et al.* [2] developed an intelligent model to control the drum water level. The comparison of different tuning techniques of PID controller has been done in terms of distinct parameters such as rise time, settling time etc. It has been found that the internal model controller (IMC) has better performance than both of these Tyreus Lubyen and Ziegler Nichols PID tuning techniques.

Jacob *et al.* [31] designed a set point filter and PID controller in double feedback loop for conical tank to reduce the undesired percentage overshoot from the response of control system.

Chermakani *et al.* [32] developed a simple method of set-point filter for designing PID controller. The coefficient of set-point filter is based on zeros of the controller. The proposed method yields better results than Ziegler Nichols method. One main drawback of the method is set-point filter coefficient is not optimum. By varying the filter coefficient can help to achieve the overshoot to the desired level.

Solanki *et al.* [33] proposed an IMC based PID tuning method for the two element control strategy. Vijula *et al.* [34] developed a model based controller for nonlinear conical tank process. Two controllers including PID and IMC based PID controller are compared and it has been found that later has better rise time and settling time than conventional PID controller.

Gireesh *et al.* [35] designed a PI controller using different tuning methods for nonlinear conical tank process to maintain the desired value of liquid level in tank. A comparative study of different tuning methods including Ziegler Nichols, Cohen-coon, CHR and Kappa-Tau have been made and it has been found that CHR method shows better results than the other methods in terms of different performance indicators.

Rodriguez *et al.* [36] implemented a design of optimal feed-forward compensators for integrating plants. The proposed method is designed for the cases where the ideal feed-forward controller is not physically implemented because of the integrating dynamics present in the process and it cannot be possible to reject the disturbance effect from the feedback error.

Maurya *et al.* [37] presented a comparative analysis of various controllers for the boiler drum level control including PID and FLC (sugeno) and FLC (mamdani). It has been found that FLC (sugeno) has better performance in terms of settling time, rise time than other type of controllers. EI-Guindy *et al.* [38] developed a linear quadratic regulator (LQR) control strategy to optimize the level of water and steam pressure control performance of a boiler drum unit.

Rodriguez *et al.* [39] designed feed-forward compensators for the systems having right half plane zeros to enhance the disturbance rejection capability.

Kadu *et al.* [40] designed a self adaptive fuzzy PID controller for the inverse response of boiler drum level. The developed method performance is more effective than the internal model controller in order to minimize the overshoot and undershoot.

CHAPTER 3

CONTROL SCHEMES FOR STEAM DRUM LEVEL

3.1 STEAM DRUM LEVEL CONTROL SYSTEM

Steam drum is an essential part of boiler system in process industries. For the proper and safe functioning of boiler, there are various parameters that have to be controlled including level of steam drum, flow of feed-water and flow of steam. The pressure, temperature and level of boiler system cannot be regulated directly, but depends on the feed-water flow. The pressure or temperature in a boiler system can be maintained by controlling the flow of fuel and air whereas the level can be maintained by regulating the flow of feed water. The purpose of drum level controller is to keep the level at desired value. So there should be an optimal interface level between steam and water within the steam drum. It is essential that the level of liquid must be low enough to assure that there is appropriate separation between steam and water and high enough to guarantee that the water exists in every steam generating tube. There are various components that affect the level of steam drum. The bubbles exist under the interface level between steam and water into the steam drum due to boiling of water. The increased/decreased volume of steam bubbles leads to the variations in water level that result in the phenomenon of 'false water level'. Another component that affects the water level is the steam drum pressure. The contraction or expansion of steam bubbles depend on the variations in steam drum pressure due to changes in the steam demand. As the demand of steam increases, it will cause the steam drum pressure to fall that result in the expansion of steam bubbles. The water level of steam drum rises due to the increased volume of steam bubbles. This phenomenon of rise in water level due to the decreasing of drum pressure is called as 'shrink effect'. A decrease in water level as a result of increase in drum pressure is called as 'swell effect'.

3.2 TYPES OF STEAM DRUM LEVEL CONTROL SYSTEM

There exist three types of control systems to regulate the steam drum level i.e. **single element** drum level control system, **two element** drum level control system and **three element** drum level control system.

3.2.1 SINGLE ELEMENT DRUM LEVEL CONTROL

Single element drum level control is the easiest strategy for controlling the water level of steam drum. In this approach, the level is being measured that helps in controlling the flow of feed water to maintain the steam drum level. This control strategy is suitable for small boilers that have low and moderate variations in load/disturbances. As the demand of steam increases, the pressure in the boiler drum decreases that will cause a rise in the level of steam drum. The increase in drum level sends a false water level signal to lower the flow of feed water when it should increase actually to maintain the desired level. This phenomenon is called as 'swelling' of drum level. When there is a decrease in steam demand, the drum pressure increases and result in lowering the level of steam drum sending a false water level signal to increase the flow of feed water when it should decrease actually to maintain the desired level. This phenomenon of decreasing water level is called as 'shrinking' of drum level. The drawback of this approach is that level of steam drum is affected by uncontrolled feed water and steam disturbances. Figure 3.1 shows the control strategy for single element drum level control [2].

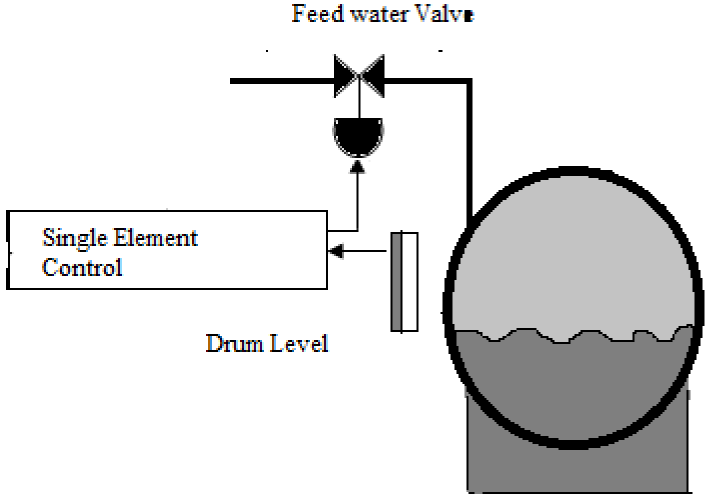

Figure 3.1 Single element drum level control

3.2.2 TWO ELEMENT DRUM LEVEL CONTROL

Two element drum level control consists of a feed forward controller to reduce the steam flow disturbance effect. The control strategy can be used for any boiler size and is effective for the boilers with moderate variations in load. This approach employs two variables including steam flow and drum water level for the manipulation of feed water control valve. The water level of steam drum is being measured and the output response is compared with the desired set point. The corresponding error is then fed to a summer as one of the two variables. The second variable to a summer is the flow of steam. The output of the summer is then given as the control signal to the feed water control valve. Since flow of the steam is dynamic, rise or fall of steam demand can be sensed by this approach before affecting the drum level. The control output is then added or subtracted to stabilize the effect of drum level controller on feed water control valve. During steady changes in load, the feed water control valve is influenced by the drum level controller and helps in maintaining the drum level to a desired set point. The drawback of this strategy is that the disturbances due to steam drum pressure and variations in load cannot be adjusted in feed water supply as this variable is not measured in this control strategy. Figure 3.2 shows the control strategy for two element drum level control [2].

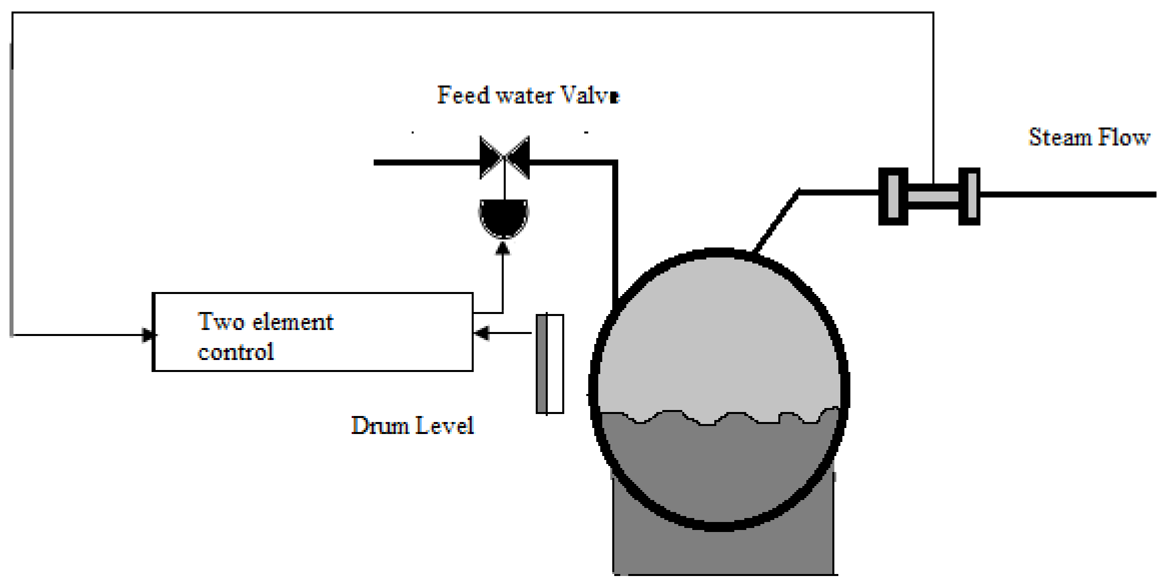

Figure 3.2 Two element drum level control

3.2.3 THREE ELEMENT DRUM LEVEL CONTROL

Three element drum level control is the most common boiler drum level control strategy. For the control systems where load is greater than 30%, it is effective to use three element drum level control so that shrinking and swelling effects can be taken care of. Figure 3.3 shows the control scheme of three element drum level control. The shrink and swell introduces the phenomenon of false water level that leads to the measurement of three parameters including drum water level, feed water flow and steam flow. With the addition of feed water flow and steam flow measurement in the control system, one can easily determine any major discrepancy between the two and take the control action to maintain the water level. The same results can be attained by using two element control.

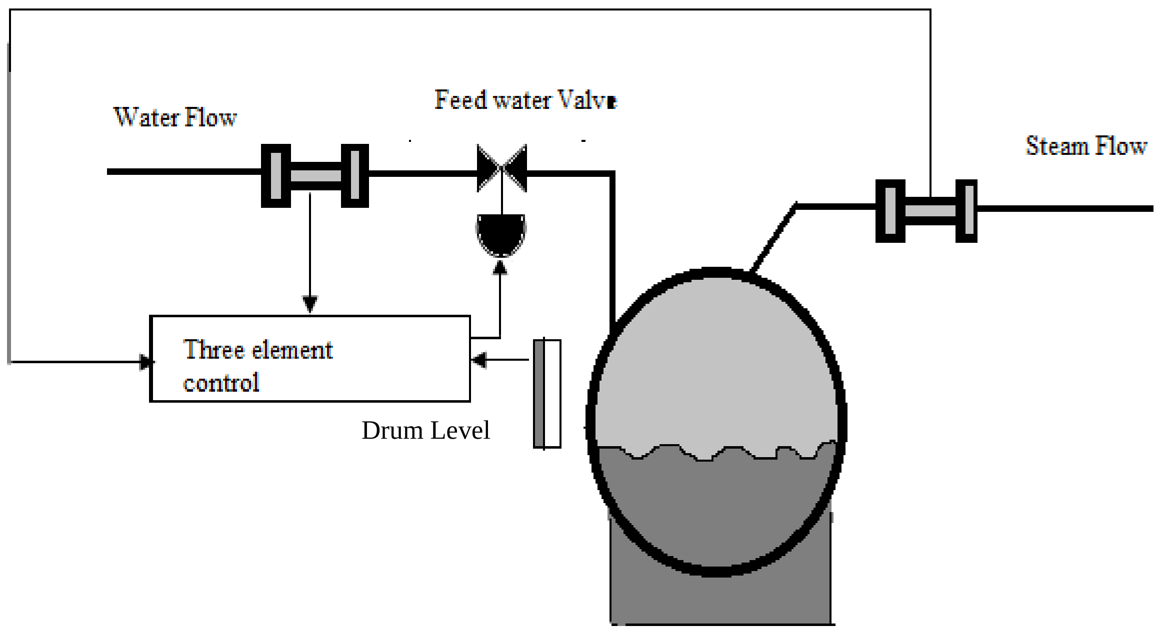

Figure 3.3 Three element drum level control

But there are some disadvantages of two element control such as it cannot change for the load disturbances take place in feed water supply. Secondly, the phasing interaction between the drum level and feed water flow cannot be eliminated by the two element control. Thus in order to deal with these issues, three element steam drum level control is used in which a third variable feed water flow rate is added which is used to manipulate the feed water control valve. The output of two element drum level controller is cascaded with feed water flow controller. The steam flow act as the set point to the feed water controller and feed water flow is used as the process variable. Thus amount of steam leaving the drum results in the addition of equal quantity of feed water to the drum. The three element drum level control strategy is effective for rapid variations in load because it can easily handle the balance between feed water flow and steam flow [2].

3.3 TYPE OF CONTROL SCHEMES

There are various control schemes that are used in process industries. Some of them are given below:

1. Feedback control strategy
2. Feed-forward control strategy
3. Cascade control strategy

3.3.1 FEEDBACK CONTROL

In a feedback control, error is obtained by comparing process variable with the desired set point. The error signal acts as an input to the controller and generates the control signal which then manipulates the plant parameters. The basic purpose of using feedback control is to maintain the output variable near to the desired value despite of all the disturbances and parameter variations in the plant. Negative feedback is preferred to eliminate the error from the system. It also makes the system performance better in terms of stability and rejects load disturbance signal. The main aim of using feedback control is to lower the system sensitivity to variations in parameter [44].

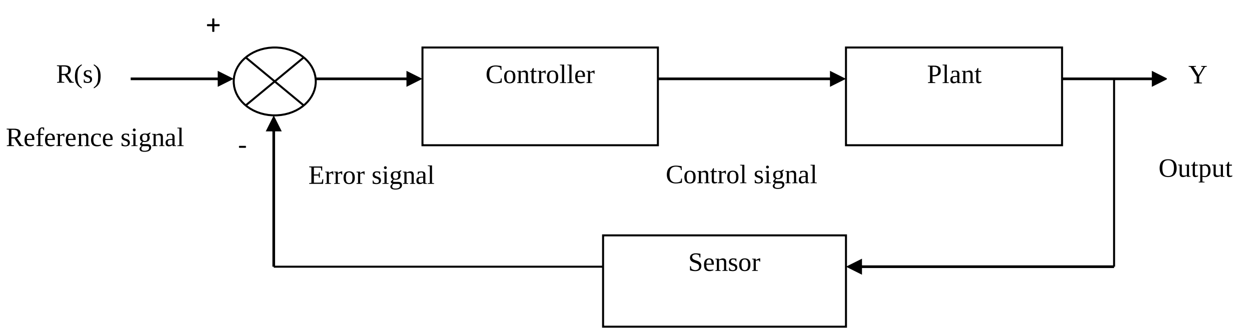

Figure 3.4 Basic structure of feedback control

3.3.1.1 ADVANTAGES:

1. Feedback controls do not need any mathematical model for the process.
2. Ability to trace the process output response and thus helps in tracing the performance of the system.
3. The unstable processes are stabilized by evaluating the output of system.

3.3.1.2 DISADVANTAGES:

1. The main disadvantage of feedback control is that it introduces the time lag into the system.
2. Corrective action is taken when there is an occurrence of deviation in the controlled variable.
3. Unable to take corrective actions for the effects of load disturbances.
4. The feedback control is not feasible for the applications where controlled variable cannot be evaluated on line.

3.3.1.3 APPLICATIONS OF FEEDBACK CONTROL

1. Flow control
2. Liquid level control in steam drum
3. Pressure control
4. Temperature control in CSTR

3.3.2 FEED-FORWARD CONTROL

The main aim of feed-forward control is to reduce the measured disturbance effect from the system and make the system stable. The feed-forward control predicts the effect of load disturbance and takes the control action before the process has been affected. In order to enhance the system performance, both feedback and feed-forward controllers are combined. Feed-forward controllers eliminate some specified disturbances and not all the disturbances that exist in a plant. Thus feed-forward controller is employed as an improvised strategy for the feedback control system against load disturbances [42].

3.3.2.1 ADVANTAGES:

1. Takes the control action against the effect of load disturbance before the output is affected.
2. Feed-forward controller does not affect the closed loop stability as feed-forward transfer function does not appear in the characteristic equation.
3. It is suitable for the systems having lag time.

3.3.2.2 DISADVANTAGES:

1. It needs the detailed knowledge for the model of process.
2. Feed forward controller is sensitive to the variations in process parameter.
3. It cannot handle unmeasured disturbances.
4. It needs recognition of all the possible disturbances.

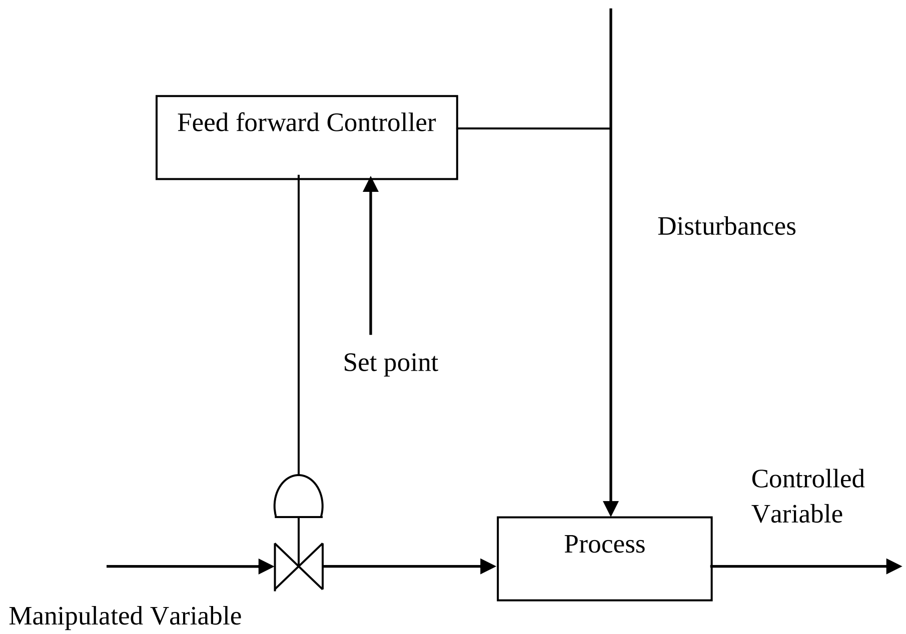

Figure 3.5 Basic structure of feed-forward control

3.3.2.3 EXAMPLE OF FEED-FORWARD CONTROL

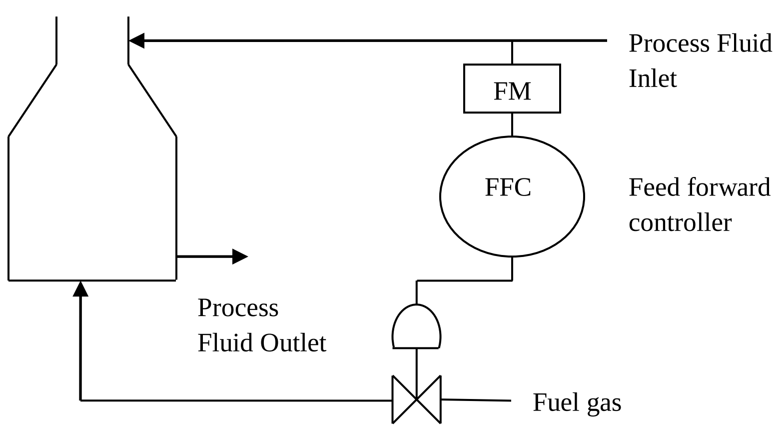

Figure 3.6 Feed-forward control of temperature based on fluid flow rate [47]

Figure 3.6 shows the structure of a fired furnace system that helps in heating fluid stream. The fluid flow rate is one possible disturbance that acts on the system. If the fluid flow rate rises to 30% then necessary heat duty should also increase by the same amount. The main aim of the feed-forward control strategy is to alter the flow rate of fuel gas when there is a variation in the fluid flow rate is identified [43].

3.3.3 CASCADE CONTROL

Cascade control is a multiple control loop system that is basically used to control one primary variable with the use of two measurement signals. Cascade control consists of two controllers i.e. primary controller also known as master controller and secondary controller also known as slave controller. The output of the master controller acts as the set point to the slave controller whereas the secondary controller output is employed to manipulate the control variable. The secondary controller works faster than the primary controller. The primary controller is not affected by the disruptions from the fast variations of secondary controller.

3.3.3.1 ADVANTAGES:

1. Eliminates the dead time effect from the system.
2. Ability to recover faster from disturbances
3. Enhances the dynamic performance of the system.

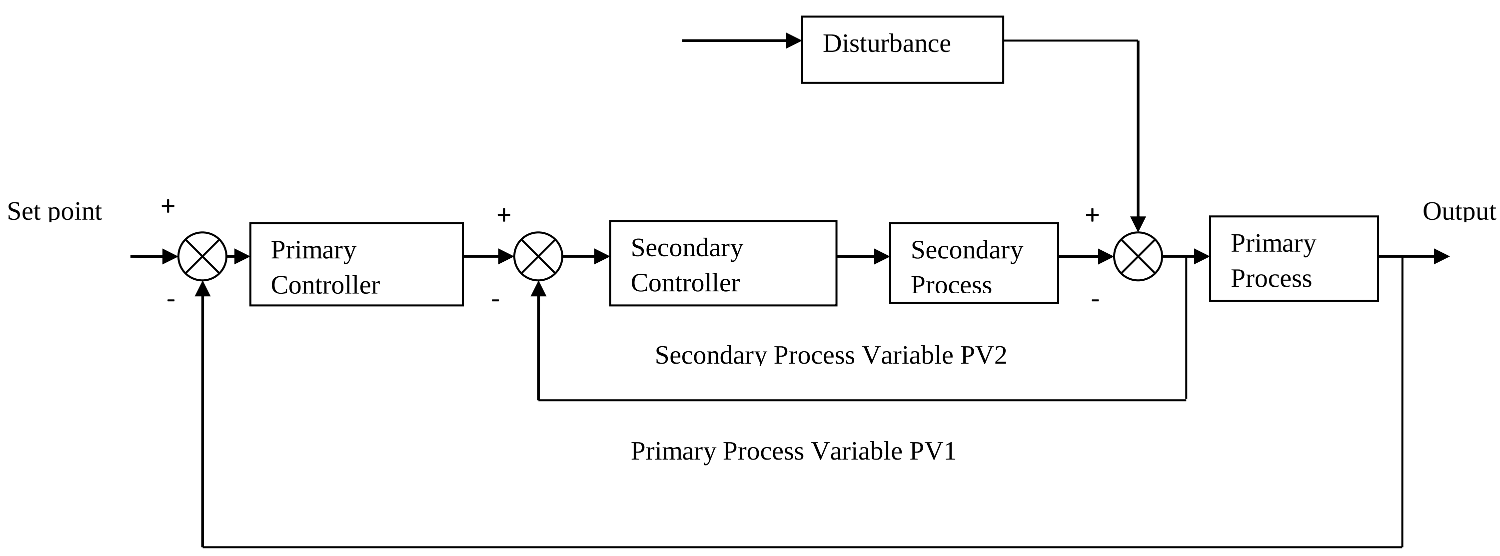

Figure 3.7 Basic structure of cascade control

3.3.3.2 DISADVANTAGES:

1. Cascade control introduces the complexity into the system.
2. The tuning of cascade controller is difficult as there are variations in set point and system parameters.
3. Cascade control needs more equipment that will make a rise in its cost.

3.3.3.3 EXAMPLE OF CASCADE CONTROL

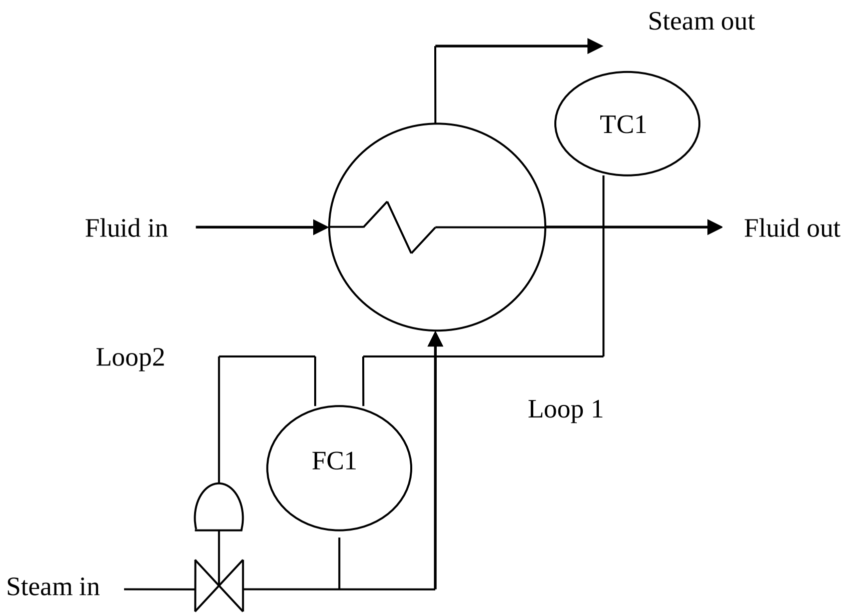

Figure 3.8 Cascade control of heat exchange system

Figure 3.8 shows the structure of heat exchanger using cascade controller in which fluid is heated with the help of steam to maintain the specified temperature. The whole process is regulated by the temperature controller that computes the fluid temperature and accordingly opens or closes the valve to provide the required amount of steam to maintain the desired temperature. If the steam flow rate changes, the controller will be unable to identify it and opens or closes the valve to the same extent anticipating getting the desired steam flow rate but will not get the same. Thus single loop control system will be unable to keep the fluid at specified temperature. The cascade control is used to eliminate the steam flow rate fluctuations as an inner loop to maintain the outer loop variable i.e. fluid temperature.

3.4 PID CONTROLLER

PID controller is one of the most widely used controllers in industrial applications. Many of the industries employ PID controllers because of the following reasons:

1. Robustness behavior: PID controller is a robust controller means it provides a good behavior despite of the variations in plant parameters due to ageing and environmental conditions.
2. Simplicity: PID controller is a simple controller because it has only few parameters that are easy to adjust.
3. Ease in implementation and maintenance.

PID controllers are still widely used in process industries even after the development of various advanced process control strategies, predictive controllers etc. PID controller is also known as three term control as it consists of three distinct variables including proportional, integral and derivative. It can also overcome some important issues like integrator windup and actuator saturation. PID controller maintains the output response in such a way that there is a zero error between output and input.

The behavior of three term control is explained as:

The **proportional component** gives the output which is proportional to the current error that is the difference between output and set point. The resulting error is multiplied with the proportional gain to get the desired output. If the error is zero then the output of the controller will be zero.

Proportional term is given by,

$$u(t) = k_p e(t) \qquad (3.1)$$

This controller requires the manual reset because it never reaches the steady state condition. Proportional controller provides the stabilized output but there is always exists some steady state error. The increase in proportional gain will increase the control system response speed and also decrease the steady state error. Increasing the proportional gain to a large extent will make the process variable more oscillatory and results in the instability of the system.

Integral component provides the required control action to remove the steady state error/offset from the output response of the system. It integrates error over a period of time to remove steady state error. The response of the integral component will rise over time until the error approaches zero value. If the integral action is too small then it will cause overshoot, oscillation and instability problems.

Integral term is given by,

$$u(t) = k_i \int_0^t e(t)dt \tag{3.2}$$

Smaller integral time values will have stronger integral effect on the system response. If the value of integral gain is small then it will reject the disturbance but after a long time. If the value of integral gain is large then it will make the response oscillatory. PI controller is used particularly where high speed is not required. The main drawback of an integral controller is that it does not have the capability to predict the future behavior of error. Figure 3.9 shows the basic structure of PID controller.

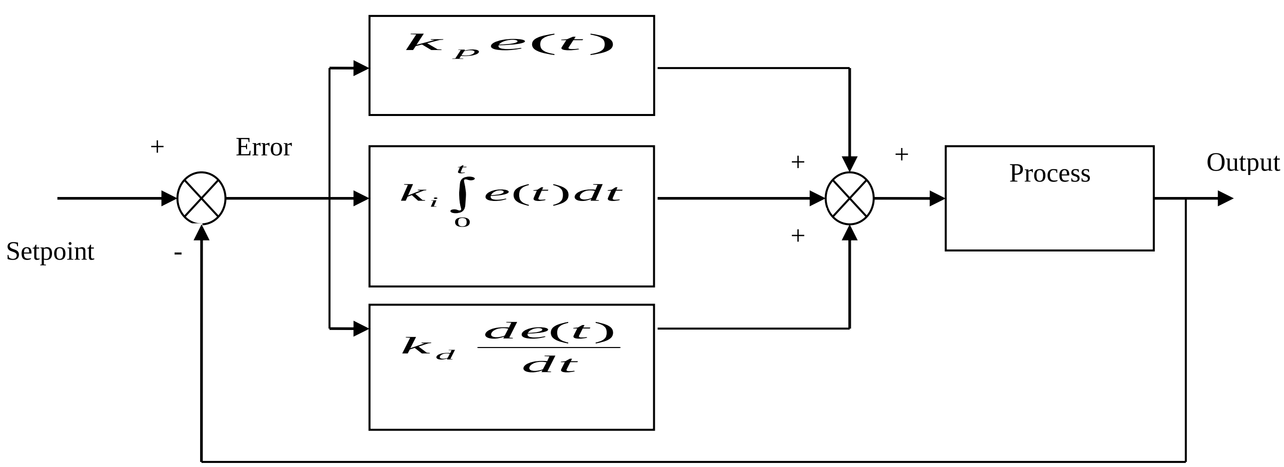

Figure 3.9 PID block diagram

The **derivative controller** anticipates the future behavior of error because the derivative component response is proportional to rate of change of error. The derivative action prevents the system from overshoot and eliminates oscillations. Most of the control systems use smaller derivative time because the response of the derivative component is highly sensitive to noise.

Derivative term is given by,

$$u(t) = k_d \frac{de(t)}{dt} \tag{3.3}$$

Larger the value of derivative component, more rapidly the controller will respond to the changes in process value due to the presence of disturbances.

A large number of PID controllers are used in industrial applications. The desired response characteristic in a control system is attained by the proper tuning of controllers. It is desired to tune the controllers individually to get a better and robust performance. It is so tedious and time taking to tune a controller manually as the performance of the system depends on the experience of the engineers. In process industries, there are many controllers that are poorly tuned and this problem has been overcome by the tuning of PID controller automatically.

3.4.1 TUNING OF PID CONTROLLER

There are two methods that are employed for tuning the parameters of P, PI and PID controllers including Ziegler Nichols closed loop method (or Ultimate Cycling method) and the Ziegler Nichols open loop method (or Process reaction-curve method). The Ziegler-Nichols closed-loop is the mostly employed method among these two methods. The definition for the control system stability given by Ziegler and Nichols is as: The ratio of the amplitudes of subsequent peaks in the same direction is approximately ¼.

It is not necessary for a control system to get the exact amplitude ratio of ¼ after tuning with one of the Ziegler and Nichols methods.

3.4.1.1 ZIEGLER NICHOLS CLOSED LOOP METHOD

The tuning procedure is as follows:

- Increase the proportional gain until the closed loop response shows the continuous oscillations. If the value of controller gain is large enough then there is an instability introduced into the system and for the smaller values of controller gain, system becomes stable.

- The proportional gain value at which the system starts oscillating is called as ultimate gain, k_{cr} and the peak to peak time period between successive peaks is called as critical gain, P_{cr} .
- Depending on the type of controller used, the tuning parameters for the different controllers are given in Table 3.1 [43].

Table 3.1 Ziegler Nichols Closed Loop Tuning Method [43]

PID Type	$\boldsymbol{k_c}$	$\boldsymbol{\tau_i}$	$\boldsymbol{\tau_d}$
P	$0.5k_{cr}$	∞	0
PI	$0.45k_{cr}$	$P_{cr}/1.2$	0
PID	$0.6k_{cr}$	$P_{cr}/2$	$P_{cr}/8$

3.4.1.2 ZIEGLER NICHOLS OPEN LOOP METHOD

Ziegler Nichols open loop method was proposed for use on dead time as well as integrating processes. This method gives the information about the three process parameters: process gain, delay time and time constant that are used to find out the tuning parameters of P/PI/PID controllers.

The tuning procedure is as follows:

- Firstly the controller is in manual mode and waits until the process reaches the steady state.
- The controller output is made to a step change and wait until the process variable reaches a new value and then note down the process output response.
- The process gain is calculated as:

  k_p =Variation in process variable (in %)/Variation in controller output (in %)
- Determine the maximum slope on process variable response curve. The slope exists at the point from where process variable starts curving downward and stops curving upward. This point is called as point of inflection. Draw a tangent through inflection point to the

process variable response curve. Enlarge this tangent until it intersects the original process variable level. Record the value of time at this intersection point.

- The dead time can be measured as:
  θ =Difference in time between the step change in controlled output and the intersection point.
- Time constant can be determined as:
  τ_p =Difference in time between intersection at the end of dead time and the process variable reaching 63% of its total change.

Table 3.2 Ziegler Nichols Open loop tuning method

PID Type	k_c	τ_i	τ_d
P	$\frac{\tau_p}{k_p\theta}$	-	-
PI	$0.9\frac{\tau_p}{k_p\theta}$	3.3θ	-
PID	$1.2\frac{\tau_p}{k_p\theta}$	2θ	0.5θ

3.5 IMC BASED PID CONTROLLER

Internal Model Control is used to design and tune the controllers. IMC based PID controller has the best ability of tracking the set point but the disturbance rejection is poor for the processes with the smaller time delays. In process industries, model based control systems are used to get the desired set points and reject external disturbances [44].

The structure of IMC shown in Figure 3.10 consists of a process (G), model of the process (G*) and an IMC controller (C).

Steps for the designing of IMC controller are:

1. Firstly, model of the plant G*(s) is divided into two components as

$$G^*(s) = G^*_+(s)G^*_-(s) \tag{3.4}$$

where, $G_{+}^{*}(s)$ is noninvertible component that consists of all the time delays and non-minimum phase elements whereas $G_{-}^{*}(s)$ is invertible component that generally contains the transfer function with minimum phase characteristics with no predictive term.

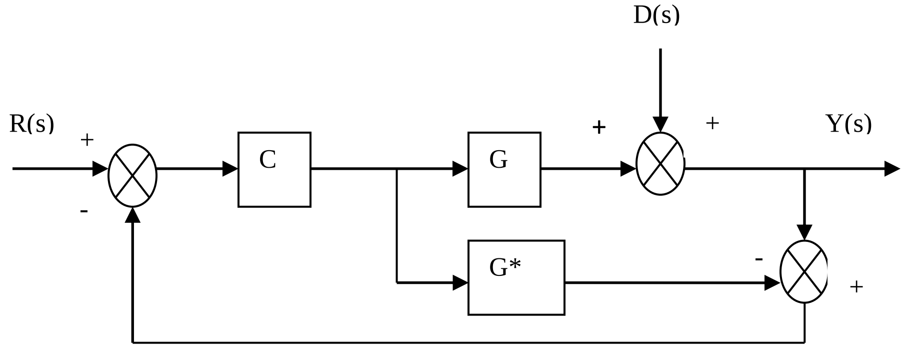

Figure 3.10 Block diagram of IMC system [52]

2. A low pass filter *f*(s) is cascaded with $G_{-}^{*}(s)$ for the stability of the control system. The IMC controller is then given by,

$$C(s) = G*_{-}^{-1}(s) f(s) \tag{3.5}$$

For the designing of a PID controller for a general feedback control system, a rearranged structure of IMC is shown in Figure 3.11 where,

$$Q(s) = \frac{C(s)}{1 - G*(s)C(s)} \tag{3.6}$$

$$C(s) = \frac{Q(s)}{1 + G*(s)Q(s)} \tag{3.7}$$

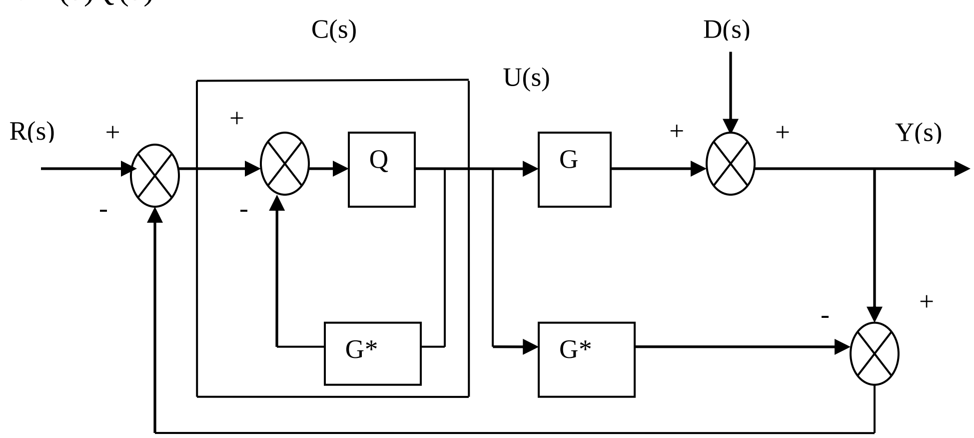

Figure 3.11 Equivalent internal model control structure [52]

The equivalent internal model control structure in Figure 3.11 is then equal to a general feedback control system in Figure 3.12.

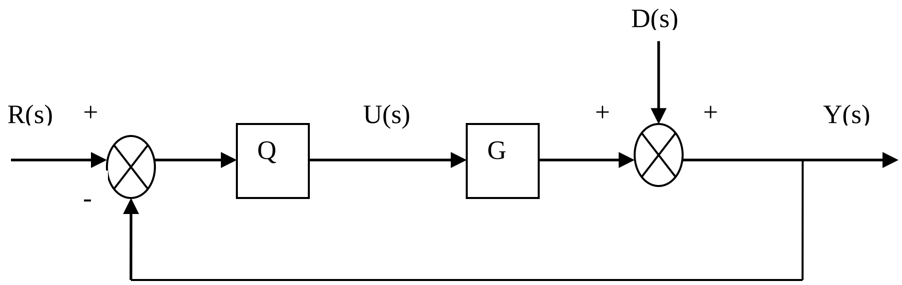

Figure 3.12 General Feedback control

The controller Q(s) can be obtained by Equations (3.5) and (3.6) as

$$Q(s) = \frac{G*_{-}^{-1}(s)}{f^{-1}(s) - G*_{+}^{-1}(s)} \tag{3.8}$$

The controller Q(s) can also be written in the following form

$$Q(s) = \frac{1}{s}\phi(s) \tag{3.9}$$

Now, $\phi(s)$ can be expanded using Maclaurin series as given in Equation 3.10

$$Q(s) = \frac{1}{s}(\phi(0) + \phi'(0)s + \frac{\phi''(0)s^2}{2!}) \tag{3.10}$$

Comparing the structure of controller Q(s) in Equation 3.10 to the general transfer function of the PID controller in Equation 3.11

$$k_{PID}(s) = k_p + \frac{k_i}{s} + k_d s \tag{3.11}$$

By avoiding the higher order terms, the PID parameters are given by:

$$k_p = \phi'(0), k_i = \phi(0),\ k_d = \frac{\phi''(0)}{2} \tag{3.12}$$

The filter $f(s)$ must be chosen accurately so that $\phi(s)$ has no zero at the origin to guarantee an acceptable performance and non-zero integral gain [44].

CHAPTER 4

PROBLEM FORMULATION

4.1 PROCESS DESCRIPTION

A steam drum is a closed vessel where steam generating tubes are exposed to heat for the transformation of water into steam. For the safe control of boiler, there must be a sufficient amount of water present in the steam drum for the generation of steam and preventing the steam drum from damage and at the same time, the level of water must be high enough to prevent the water/steam interface level from the carryover of water and impurities into the steam drum. As the steam demand increases, the flow rate of feed water into the steam drum must also increase to keep the level of water within specified limits. The boiler comprises of a combustion chamber in which burning of air/fuel takes place. There is a group of vertical tubes inside the boiler system through which feed water flows and move into the steam drum. The vertical tubes containing feed water are thermally radiated by the combustion gases and called risers as these tubes carry a mixture of steam and water. There is a horizontal cylinder drum at the top of these tubes and half of the horizontal drum is full of water. The upper section of horizontal drum consists of steam that is used for the industrial applications. Figure 4.1 shows the basic structure of a steam drum. The tubes that carry water from the steam drum to the bottom section of boilers from where water is sent to the distribution header are called as down comers. Down comers are larger in diameter because the whole amount of water flows through the down comer for evaporator before entering into the risers. The water through down comers sent to the mud drum where water and mud are separated. The water in riser tubes circulate when they are exposed to hot flue gases and the steam is released into the steam drum. The generated steam is passed to the super heaters from where the super heated product is sent to the procedure where heat is removed. The liquid is then returned to steam drum after preheating and the whole cycle begins again.

The level of steam drum is given by,

$$h = \Delta p + H(\rho_s - \rho_h) + (\rho_w - \rho_s) \tag{4.1}$$

where

h = Steam drum level

Δp = Differential pressure

H = Distance between low and high taps of steam drum

ρ_s = Saturated steam density

ρ_h = Water density in wet leg

ρ_w = Saturated water density

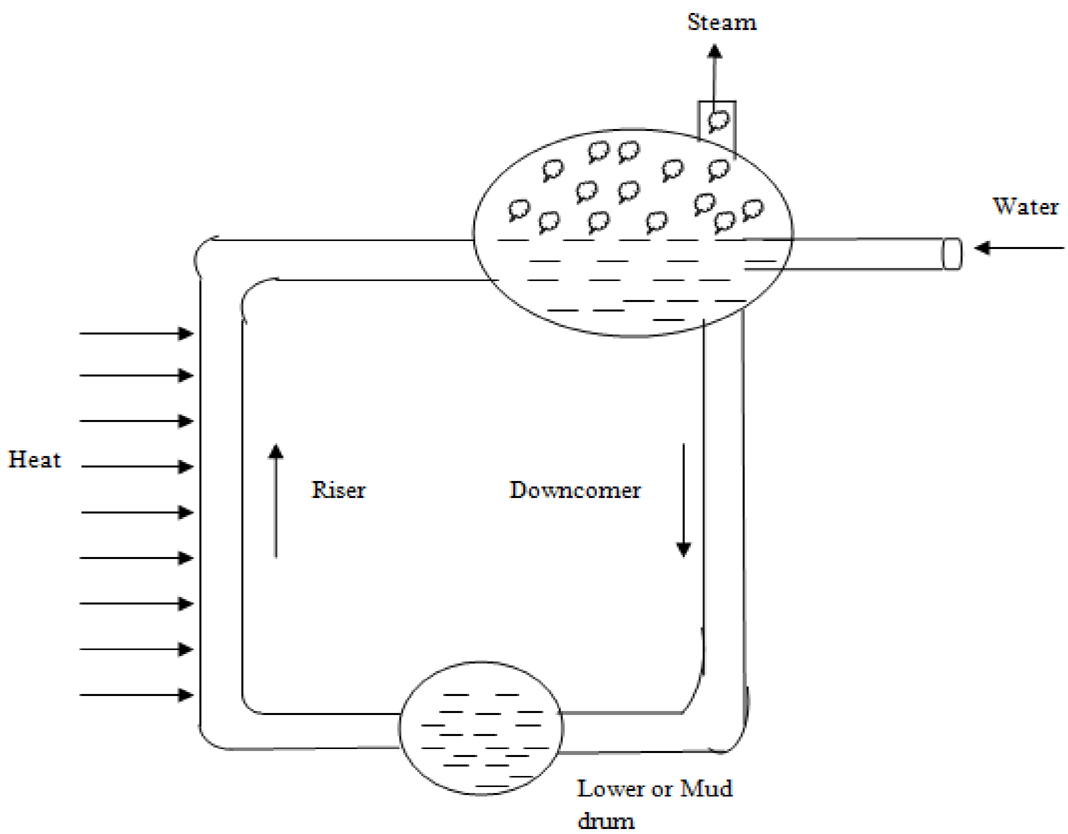

Figure 4.1 Steam Drum

4.2 PROBLEM DEFINITION

In process industries, three main parameters are to be controlled including level of fluid, steam out flow, and feed water flow for proper operation of boiler. The temperature, pressure and level cannot be controlled and thus flow is the only parameter that we can control.

The steam drum is an essential part of boiler in industrial applications. For the safe and efficient operation of boiler, the level of steam drum must be regulated and maintained. For the level control of steam drum, a conventional three element PID controller works well when there is no process disturbance but in the presence of process disturbance the controller does not work well because of inadequate amount of knowledge available for the gains of the controller to cope with the disturbances. Also there are number of papers describing IMC based PID control scheme for the drum level control but this method introduces the overshoot into the system. Thus it is required to find out some different control scheme to maintain the level of steam drum. Double feedback loop method is used along with a set point filter as a different control scheme for steam drum level control and then compares the results with the conventional methods.

4.3 SHRINK/SWELL EFFECT

The process of generating steam from the boiling water is an important procedure for the industrial applications. The steam drum is an essential part of boiler. It has three main objectives: 1) provides space for the boiling water 2) provides surface area for the steam bubbles that are generated from the boiling water 3) provides sufficient volume of water so that there is thermal intermixing of the cooler drum water with the hotter water at the interface. The main aim of level controller is to keep the level of steam drum at constant value. So there should be an optimal interface level between steam and water within the steam drum. It is essential that the level of liquid must be low enough to assure that there is appropriate separation between steam and water and high enough to guarantee that the water exists in every steam generating tube.

The interface level is exposed to several steam drum disturbances such as temperature of feed water, steam drum pressure. Due to the changes in load demand, the steam pressure drops or raises that result in the transient changes in the water level of steam drum due to the contraction or expansion of bubbles in steam drum water. As there is an increase in steam demand, the level of steam drum rises due to increase in the volume of steam bubbles. This increased volume of steam bubbles is due to fall of steam drum pressure that results in increase of steam drum level. This false increase in level reduces the flow of feed water into the steam drum. Once the steam drum pressure returned to its true value, the expanded steam bubbles start contracting and this result in the sudden drop of water level. The level control loop will increase the flow of feed water to balance the water level of steam drum that flooded the boiler with cold water. Many of the steam bubbles get collapsed in the boiler and there is a sudden drop in the boiling water that will result into a low level alarm.

With the addition of feed water flow and steam flow measurement in the control system, one can easily determine any major discrepancy between the two and take the control action to maintain the water level. The same results can be attained by using two element control. But there are some disadvantages of two element control such as it cannot change for the load disturbances take place in feed water supply. Secondly, the phasing interaction between the drum level and feed water flow cannot be eliminated by the two element control. Thus in order to deal with these issues, three element steam drum level control is used in which a third variable feed water flow rate is added which is employed to influence the feed water control valve. This system can handle feed water disturbances and loads that exhibit wide rate of changes regardless of boiler capacity.

4.4 METHODOLOGY

The double feedback loop methodology is employed to attain the process stability and system better performance. The internal loop is employed for achieving the process stability whereas the external loop helps in fine tracking of set point. For the tuning of outer loop controller, an internal model control (IMC) based PID method is used. The internal loop consists of a proportional controller and is tuned with the help of Ziegler Nichols method. The process transfer function for steam drum introduces an undesired percentage overshoot into the system and is removed by employing set point filter [27].

4.4.1 DESIGN OF IMC BASED PID CONTROLLER

The basic structure of double feedback loop consists of two controllers G_c and G_{c1}. The basic structure of double feedback loop is shown in Figure 4.2. G_p is the process transfer function. The inner loop controller G_c is a proportional controller and Ziegler Nichols method is used for its tuning [27]. The external loop controller G_{c1} is tuned by IMC based PID methodology that is described as:

Assume general process transfer function G_p is given by,

$$G_p = \frac{k_p(-as+b)}{fs^3+gs^2+hs+i} \tag{4.2}$$

The inner closed loop transfer function is as

$$G_{p1} = \frac{Y}{r_1} = \frac{k(-as+b)}{fs^3 + gs^2 + hs + i + k(-as+b)} \tag{4.3}$$

where, $k = k_c * k_p$

The required transfer function of closed loop is given by,

$$G_{cl}^{D} = \frac{1}{(\tau_1 s+1)(\tau_2 s+1)(\tau_3 s+1)} \tag{4.4}$$

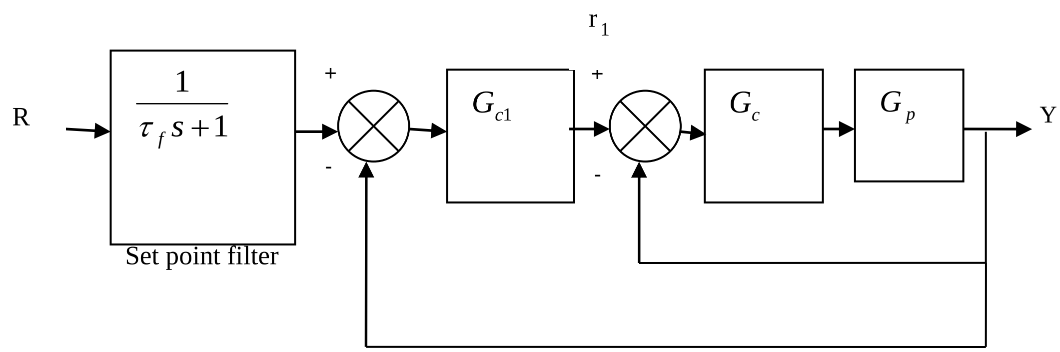

Figure 4.2 Basic structure of double feedback loop [26]

The outer loop controller G_{c1} is given by,

$$G_{c1} = \frac{1}{G_{p1}} \frac{G_{cl}^{D}}{1 - G_{cl}^{D}} \tag{4.5}$$

By putting Equations (4.3) and (4.4) in Equation (4.5) one gets

$$G_{c1} = \frac{fs^3 + gs^2 + hs + i + k(-as+b)}{k(-as+b)} * \frac{1}{(\tau_1 s+1)(\tau_2 s+1)(\tau_3 s+1) - 1} \tag{4.6}$$

By expanding Equation (4.6) one gets

$$G_{c1} = \frac{fs^3 + gs^2 + hs + i + k(-as+b)}{ks[b\tau_1 + b\tau_2 + b\tau_3 + s(-a\tau_1 - a\tau_2 - a\tau_3 + b\tau_1\tau_2 + b\tau_2\tau_3 + b\tau_3\tau_1) + s^2(-a\tau_1\tau_2 - a\tau_2\tau_3 - a\tau_3\tau_1 + b\tau_1\tau_2\tau_3)]} \tag{4.7}$$

Simply G_{c1} can be written as

$$G_{c1} = \frac{\phi(s)}{s} \tag{4.8}$$

where, $\phi(s)$ is given by,

$$\phi(s) = \frac{fs^3 + gs^2 + hs + i + k(-as + b)}{k[b\tau_1 + b\tau_2 + b\tau_3 + s(-a\tau_1 - a\tau_2 - a\tau_3 + b\tau_1\tau_2 + b\tau_2\tau_3 + b\tau_3\tau_1) + s^2(-a\tau_1\tau_2 - a\tau_2\tau_3 - a\tau_3\tau_1 + b\tau_1\tau_2\tau_3)]} \tag{4.9}$$

Equation (4.8) can be written in form of Laurent series as

$$G_{c1} = \frac{\phi(s)}{s} = \frac{1}{s}(\ldots + \phi(0) + \phi'(0)s + \frac{\phi''(0)s^2}{2!} + \ldots) \tag{4.10}$$

The PID controller standard form is given by,

$$G_c = k_c(1 + \frac{1}{\tau_i s} + \tau_d s) \tag{4.11}$$

Compare ‘s’ term coefficients of Equations (4.10) and (4.11), one gets

$$k_c = \phi'(0) \quad \tau_i = \frac{k_c}{\phi(0)} \quad \tau_d = \frac{\phi''(0)}{2k_c} \tag{4.12}$$

Substituting s=0 in Equation (4.9) and its derivatives one gets

$$\phi(0) = \frac{P}{Q} \tag{4.13}$$

$$\phi'(0) = \frac{P_1 * Q - Q_1 * P}{Q^2} \tag{4.14}$$

$$\phi''(0) = \frac{Q(P_2 * Q - Q_2 * P) - 2Q_1(P_1 * Q - Q_1 * P)}{Q^3} \tag{4.15}$$

where, $k = k_c * k_p$;

$P = i + kb$; $P_1 = h - ka$; $P_2 = 2g$;

$Q = k(b\tau_1 + b\tau_2 + b\tau_3)$;

$Q_1 = k(-a\tau_1 - a\tau_2 - a\tau_3 + b\tau_1\tau_2 + b\tau_2\tau_3 + b\tau_3\tau_1)$;

$Q_2 = k(-a\tau_1\tau_2 - a\tau_1\tau_3 - a\tau_2\tau_3 + b\tau_1\tau_2\tau_3)$;

Equations (4.12)-(4.15) provide the required PID parameters.

4.4.2 SET POINT FILTER DESIGN

Set point filters are designed to minimize the undesired percentage overshoot. The set point filters are mostly employed in cascade with a PID controller. There are various methods that need cumbersome calculations for the designing of set point filter and also these methods require some details about the process parameters, controller setting values and are tedious. But the present methodology needs information about the peak time and percentage overshoot of the response of system despite of the system type and order. The basic structure of set point filter is shown in Figure 4.3. G_p is the process transfer function and G_c is the controller transfer function. The set point transfer function is given by $\frac{1}{\tau_f s + 1}$, where τ_f is the filter time constant [23].

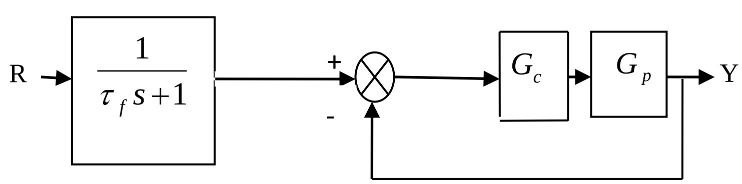

Figure 4.3 Basic structure along with set point filter [21]

Steps for the designing of set point filter are as follows:

(a) Record the actual percentage overshoot (M_{p1}) and peak time (t_{p1}) for the closed loop response of a process.

(b) The response of actual closed loop can be approximated by the transfer function of first order system that will provide a required overshoot for the desired closed loop response.

(c) The assumption for the first order system is due to the fact that the response of the closed loop will move through the percentage overshoot (M_{p1}) only when the peak time of actual closed loop response is equivalent to first order system time constant [23].

The process gain of the approximated first order system is given by,

$$k = \frac{M_{p1}}{0.6321} \tag{4.16}$$

The approximated first order time constant is given by,

$$\tau = t_{p1} \tag{4.17}$$

(d) Record the percentage overshoot (M_{p2}) and peak time (t_{p2}) for the desired closed loop response.

(e) The filter time constant (τ_f) is given by,

$$\tau_f = \tau\left(\frac{k - M_{p2} - k * e^{-t_{p2}/\tau}}{k - M_{p2}}\right) \tag{4.18}$$

Equation 4.18 gives the required filter time constant for a set point filter that helps in reducing the undesired overshoot from the system response.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 SINGLE ELEMENT STEAM DRUM LEVEL CONTROL WITHOUT LOAD DISTURBANCE USING PID CONTROLLER

The steam drum process transfer function is given by [43],

$$g_p(s) = \frac{-0.25s + 0.25}{2s^2 + s} \tag{5.1}$$

The valve transfer function is given by [43],

$$g_v(s) = \frac{1}{0.15s + 1} \tag{5.2}$$

The water level of steam drum is regulated with single element control strategy using conventional PID controller. In single element steam drum level control, level is being measured and helps in controlling the feed water flow to maintain the steam drum level. The conventional PID controller is tuned by Ziegler Nichols method whose parameters are given by:

Proportional gain (k_p) =2.094

Integral gain (k_i) =0.425

Derivative gain (k_d) =1.702

The simulink model of single element steam drum water level control using conventional PID controller is shown in Figure 5.1. In simulink model, step block is used to represent the desired level of the steam drum, sum block is used to compare the set point with the process variable and the resultant error acts as the input to the PID controller that manipulates the parameters k_p, k_i and k_d to achieve the desired output. The manipulation of these parameters accordingly opens or closes the valve. The feed water then balances the level of steam drum. Here steam load disturbance is not considered.

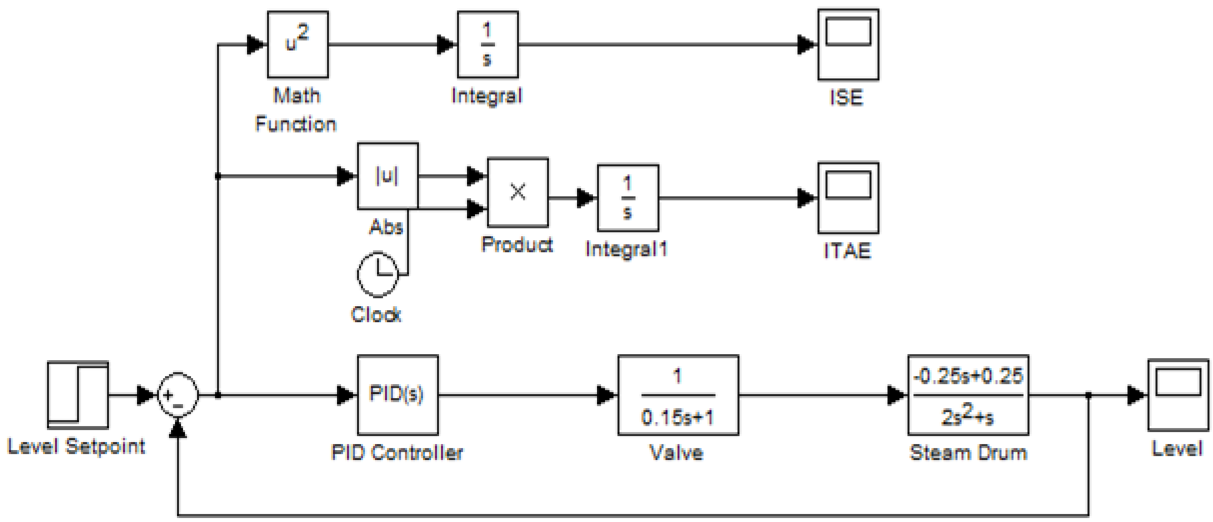

Figure 5.1 Single element steam drum level control using conventional PID controller

5.2 SINGLE ELEMENT STEAM DRUM LEVEL CONTROL WITHOUT LOAD DISTURBANCE USING IMC-PID CONTROLLER

An IMC based PID controller is employed to regulate the level of steam drum with single element control strategy. For the integrating process with inverse response, an IMC-based PID controller with integral action can be designed as [43]:

$$\tilde{g}_p(s) = \frac{\tilde{k}_p(s)(-\beta s+1)}{s(\tau s+1)} \tag{5.3}$$

where $\tilde{g}_p(s)$ is process transfer function.

and IMC filter is given by,

$$f(s) = \frac{\gamma s+1}{(\lambda s+1)^2} \tag{5.4}$$

The integral action is obtained by putting $\gamma = 2\lambda + \beta$. The parameters of resulting PID controller are given by,

$$k_c = \frac{2\lambda+\beta+\tau_p}{k_p(\lambda+\beta)^2} \tag{5.5}$$

$$\tau_i = 2\lambda+\beta+\tau_p \tag{5.6}$$

$$\tau_d = \frac{\tau_p(2\lambda + \beta)}{2\lambda + \beta + \tau_p} \tag{5.7}$$

The IMC-PID controller parameters found out are:

$\gamma = 5$

$\lambda = 2$

$k_c = 3.11$

$k_i = 0.44$

$k_d = 4.416$

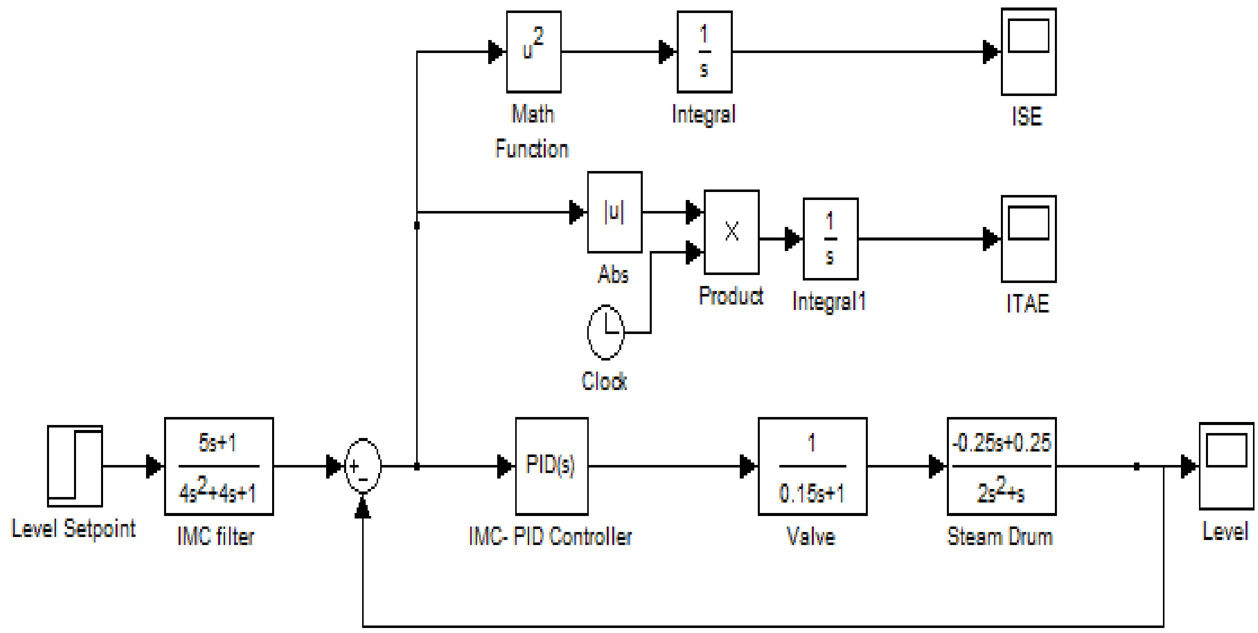

Figure 5.2 Single element steam drum level control using IMC based PID controller

The simulink model of single element steam drum water level control using IMC based PID controller is shown in Figure 5.2. In simulink model, step block is used to represent the desired level of the steam drum, sum block is used to compare the set point with the process variable and the resultant error acts as the input to the IMC-PID controller. An IMC based filter is also used for the unstable or integrating processes, or for better rejection of disturbance. Here steam load disturbance is not considered.

5.3 SINGLE ELEMENT STEAM DRUM LEVEL CONTROL WITHOUT LOAD DISTURBANCE USING DOUBLE FEEDBACK LOOP METHOD

A double feedback loop consists of two controllers including IMC based PID controller and a proportional controller for the drum level control with single element control. The double feedback loop strategy is employed to acquire the process stability and effective performance of the system. The inner loop consists of a proportional controller and is tuned with the help of Ziegler Nichols method. For the tuning of external loop controller, an internal model control (IMC) based PID method is employed. The methodology used for the designing of IMC based PID double feedback loop method is already explained in chapter 4. The calculated parameters are:

k_c =2.75; k_p =0.25;

$k = k_c \times k_p$ =0.68;

P =0.68; P_1 =0.32; P_2 =4.3;

Q =2.142; Q_1 =-0.476; Q_2 =-1.462;

k_c =0.218;

k_i =0.317;

k_d =1.25; τ_f (set point filter coefficient) =0.15;

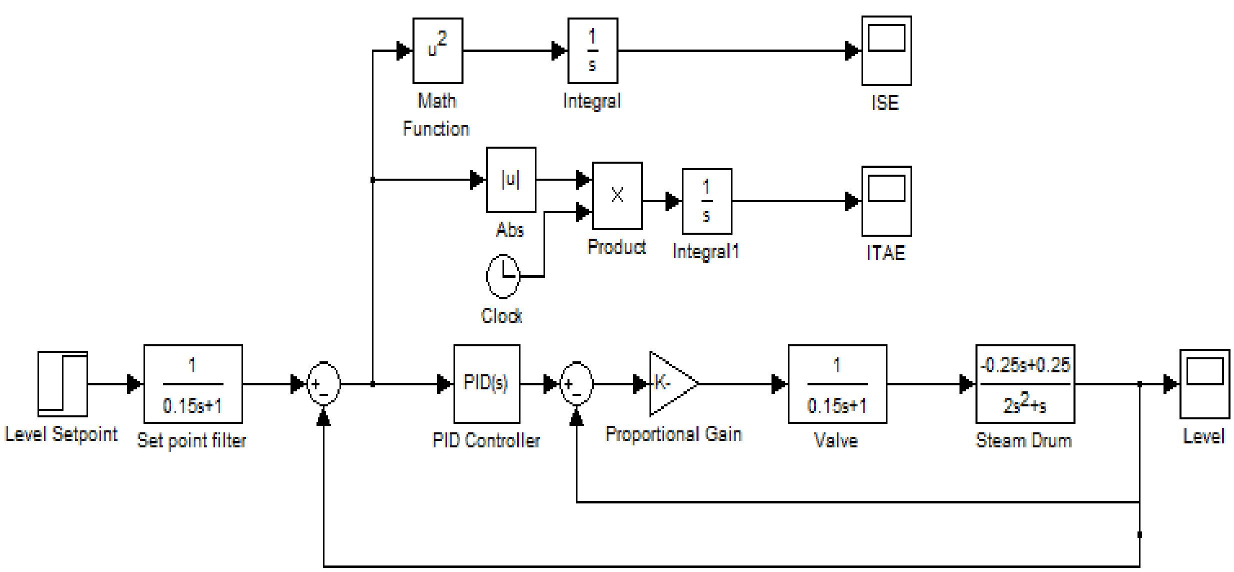

Figure 5.3 Single element steam drum level control using double feedback loop method

5.4 COMPARISON OF DIFFERENT CONTROL TECHNIQUES FOR SINGLE ELEMENT STEAM DRUM LEVEL CONTROL WITHOUT DISTURBANCE

Unit step response of single element boiler drum level control is taken using different control techniques:

- Conventional PID controller
- IMC-PID controller
- Double feedback loop method

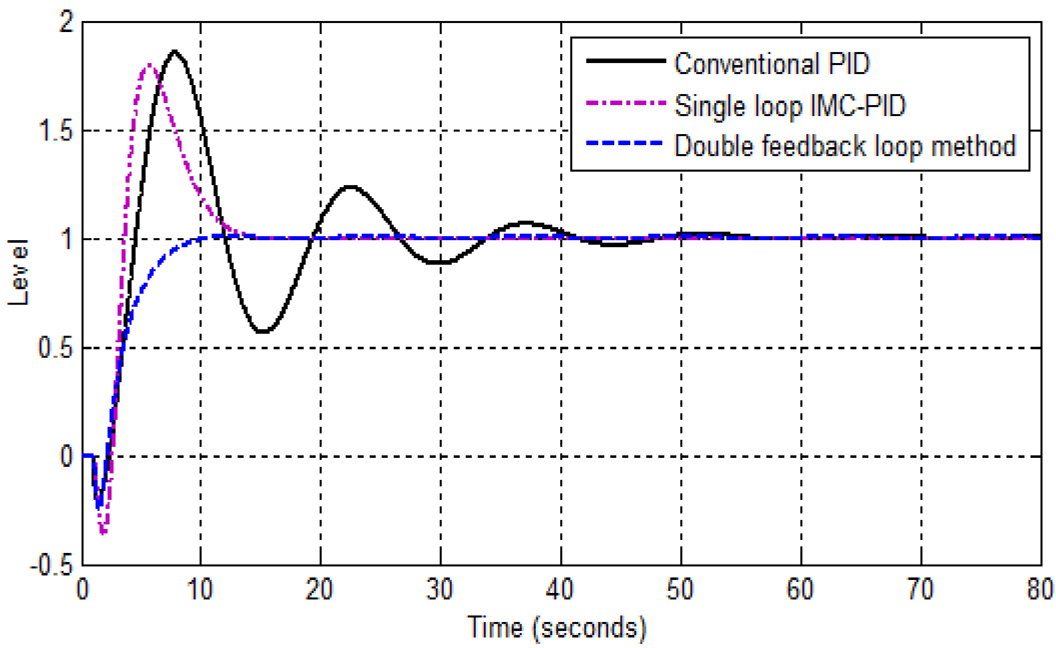

Figure 5.4 Unit Step Response of the single element Steam Drum Level control without steam load disturbance

Figure 5.4 shows the unit step responses of single element boiler drum level control using different control techniques. Three different control techniques used here are conventional PID controller, Single loop IMC-PID controller and Double feedback loop method. It is determined that double feedback loop method is more efficient than both conventional PID controller and IMC-PID controller. Table 5.1 shows comparison of different control techniques for single element drum level control using different parameters including settling time (t_s), rise time (t_r), percentage overshoot (M_p), integral time absolute error ($ITAE$), integral square error (ISE).

Table 5.1 Comparison of different control schemes using different parameters

Tuning Methods / Parameters	PID	IMC-PID	Double Feedback loop method
t_r (sec.)	1.72	0.45	4.35
t_s (sec.)	42.5	9.9	9.02
M_p (%)	85	80	0
ISE	6.17	4.59	2.32
ITAE	138.5	19.4	11.25

It is found that double feedback loop method has better settling time and percentage overshoot than the conventional methods.

5.5 SINGLE ELEMENT STEAM DRUM LEVEL CONTROL WITH LOAD DISTURBANCE USING PID CONTROLLER

The demand of steam varies in a steam drum boiler. Hence the disturbance parameter exists in the single element steam drum control. The transfer function for steam load disturbance is given by [43],

$$G_d(s) = \frac{0.25(-s+1)}{2s^2+s} \tag{5.8}$$

Figure 5.5 shows the simulink model of single element steam drum level control using conventional PID controller. In simulink model, step block is used to represent the desired level of the steam drum. Also a steam load disturbance is considered and is represented by a step block. The transfer function of steam load disturbance is taken as a second order transfer function and unity feedback is considered. The performance indices ISE and ITAE are also computed.

5.6 SINGLE ELEMENT STEAM DRUM LEVEL CONTROL WITH LOAD DISTURBANCE USING IMC-PID CONTROLLER

An IMC based PID controller is employed to regulate the level of steam drum with single element control strategy. As the demand of the steam varies in a steam drum boiler, the steam load is considered as the disturbance parameter in the single element steam drum control.

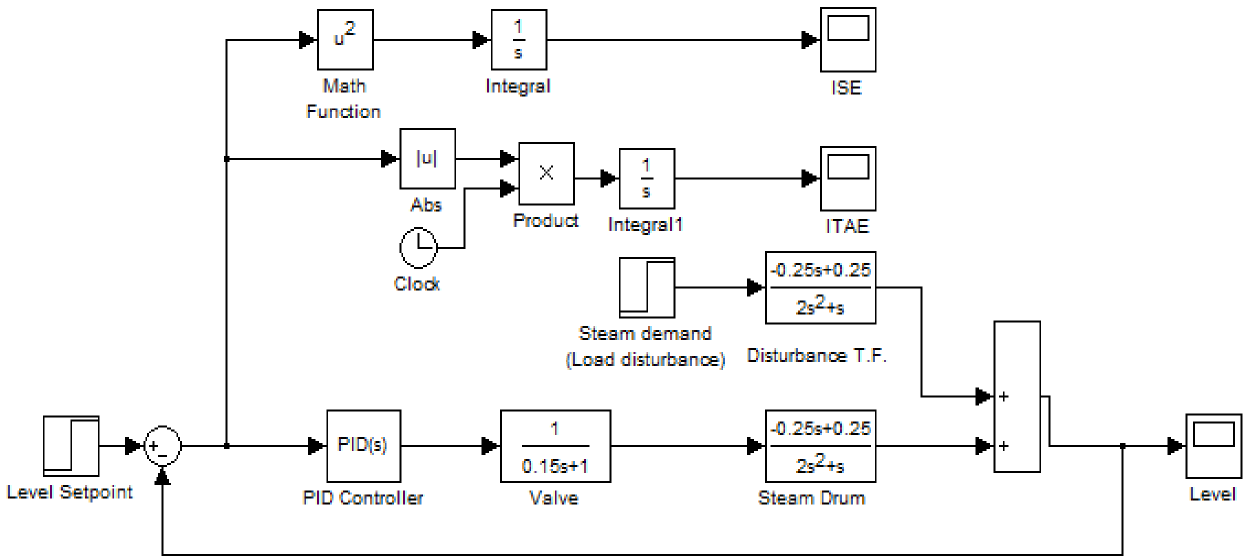

Figure 5.5 Single element drum level control using PID control with load disturbance

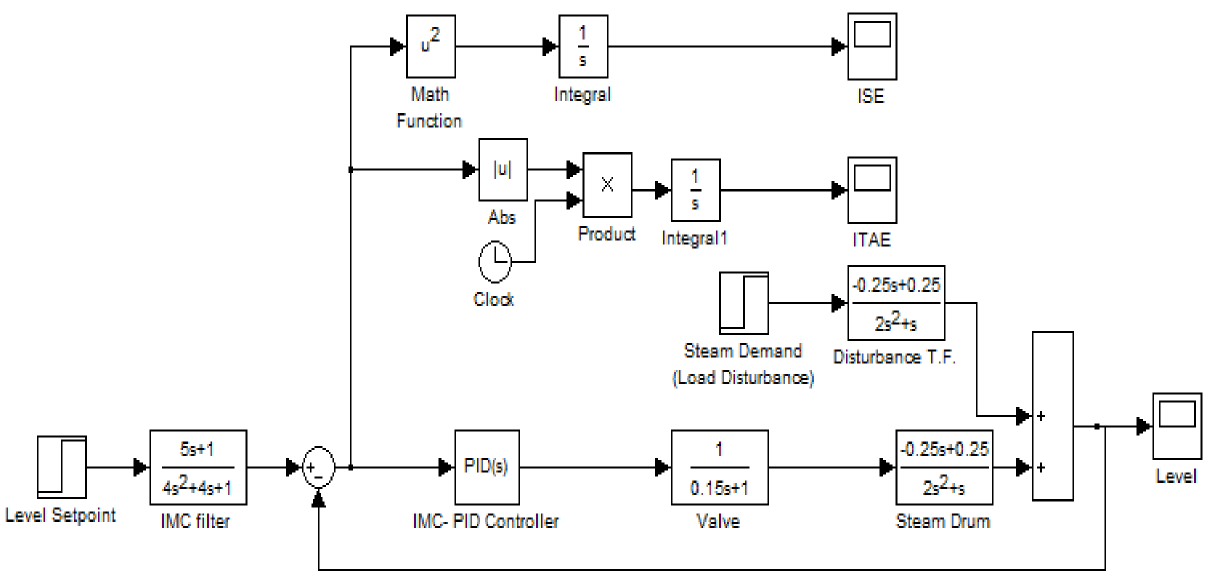

Figure 5.6 Single element drum level control using IMC-PID control with load disturbance

5.7 SINGLE ELEMENT STEAM DRUM LEVEL CONTROL WITH LOAD DISTURBANCE USING DOUBLE FEEDBACK LOOP METHOD

A double feedback loop method is employed to control the level of steam drum using single element control strategy. As the demand of the steam varies, the steam outflow is considered as the disturbance parameter in the single element steam drum level control. Figure 5.7 shows the simulink model of single element steam drum level control using double feedback loop method. Here steam load disturbance is considered and is represented by a step block.

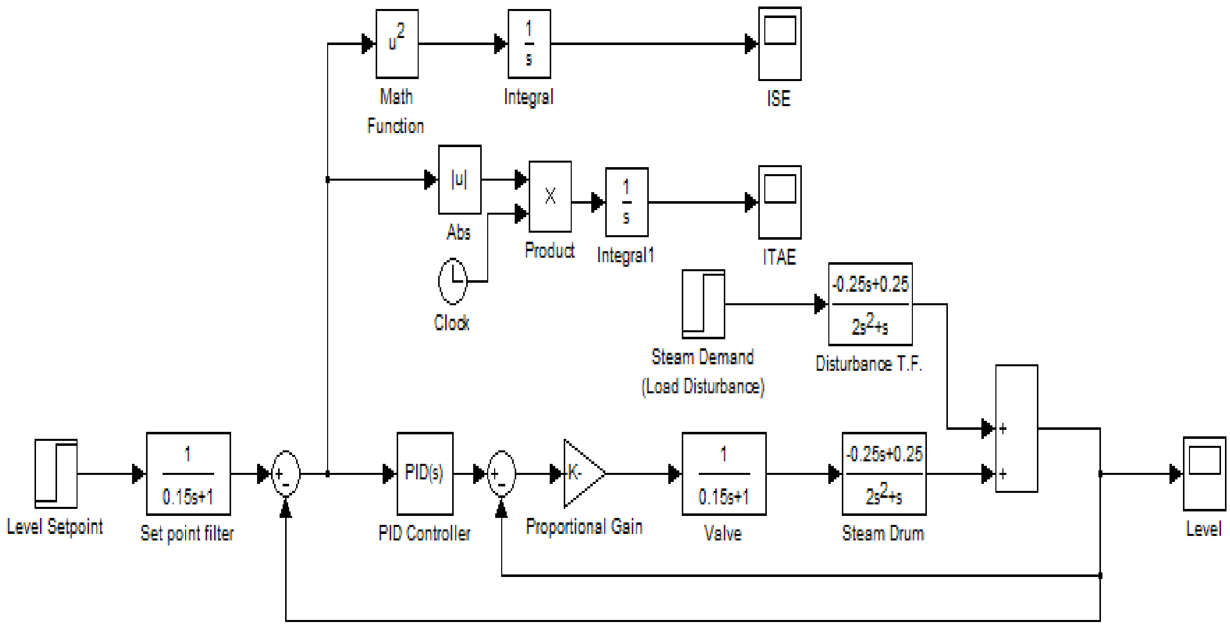

Figure 5.7 Single element drum level control using double feedback loop method with load disturbance

The internal loop consists of a proportional gain and is tuned by using Ziegler Nichols method. The external loop contoller is tuned by IMC methodology which is already described in chapter 4. A set point filter is also used along with PID controller to reduce the overshoot introduced into the system. The transfer function of steam load disturbance is taken as a second order transfer function and unity feedback is considered. The performance indices ISE and ITAE are also computed.

5.8 COMPARISON OF DIFFERENT CONTROL TECHNIQUES FOR SINGLE ELEMENT STEAM DRUM LEVEL CONTROL WITH DISTURBANCE

Unit step responses of single element boiler drum level control are taken using different control techniques. Here steam load is considered as disturbance parameter. Figure 5.8 shows the unit step responses of single element boiler drum level control with steam load disturbance using different control techniques. It is determined that the double feedback loop methodology shows better performance than both conventional PID controller and IMC based PID controller.

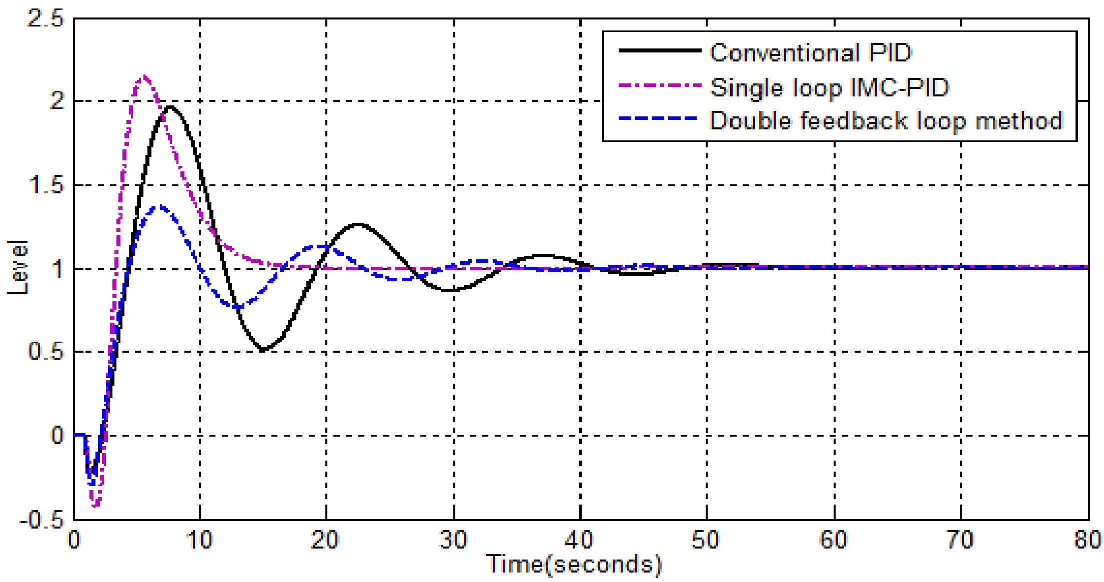

Figure 5.8 Unit Step Response of the single element Steam Drum Level control with steam load disturbance

Table 5.2 Comparison of different control schemes using different parameters

Tuning Methods / Parameters	PID	IMC-PID	Double Feedback loop method
t_r (sec.)	1.75	0.68	1.70
t_s (sec.)	24.15	11.22	8.75
M_p(%)	96.2	114	36.5
ISE	4.865	4.865	2.8
$ITAE$	153	37.15	59

Table 5.2 shows the comparison of different control techniques for single element drum level control with steam load disturbance using different parameters including rise time (t_r), settling time (t_s), percentage overshoot (M_p), integral square error (ISE) and integral time absolute error ($ITAE$). It is determined that double feedback loop method has better settling time and percentage overshoot than the conventional methods.

5.9 TWO ELEMENT STEAM DRUM LEVEL CONTROL WITHOUT FEEDWATER FLOW DISTURBANCE USING PID CONTROLLER

As the steam load disturbance is introduced into the system, it is necessary to regulate the effect of disturbance by using a feed-forward controller. Combination of feed-forward controller along with feedback controller is used to enhance the disturbance rejection capability. This design strategy is used for the cases where ideal feed-forward controller is not realizable. Thus the design of optimal feed-forward compensators for systems with right half plane zeros and integrating poles is used for the two element drum level control [36, 39].

Transfer function of feed-forward controller is given by,

$$G_{ff}(s) = \frac{-0.699s^3 - 5.3095s^2 - 4.48s - 1}{2s^3 + 5s^2 + 4s + 1} \tag{5.9}$$

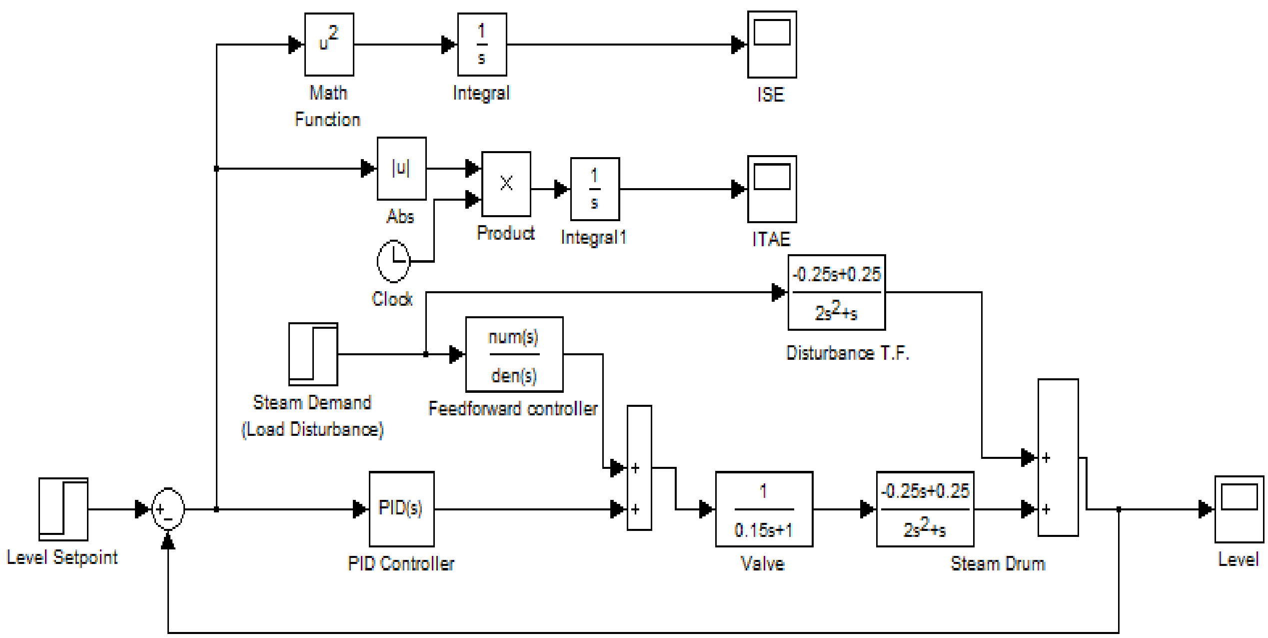

Figure 5.9 Two element drum level control using PID controller without feed water flow disturbance

Figure 5.9 shows the simulink model of two element drum level control without feed water flow disturbance using PID controller. Unit step block is used to represent the steam demand load disturbance. The performance indices ISE and ITAE are also computed in the simulink model.

5.10 TWO ELEMENT STEAM DRUM LEVEL CONTROL WITHOUT FEEDWATER FLOW DISTURBANCE USING IMC-PID CONTROLLER

Combination of feed-forward controller along with feedback controller is used to enhance the disturbance rejection capability. As the steam load disturbance is introduced into the system, it is necessary to regulate the effect of disturbance by using a feed-forward controller. Figure 5.10 shows the simulink model of two element steam drum level control using IMC-PID controller without considering feed water flow disturbance. IMC-PID controller shows the better performance than the conventional PID controller. The steam load disturbance is represented by the unit step block. An IMC based filter is also used in simulink model for the unstable or integrating processes, or for better rejection of disturbance.

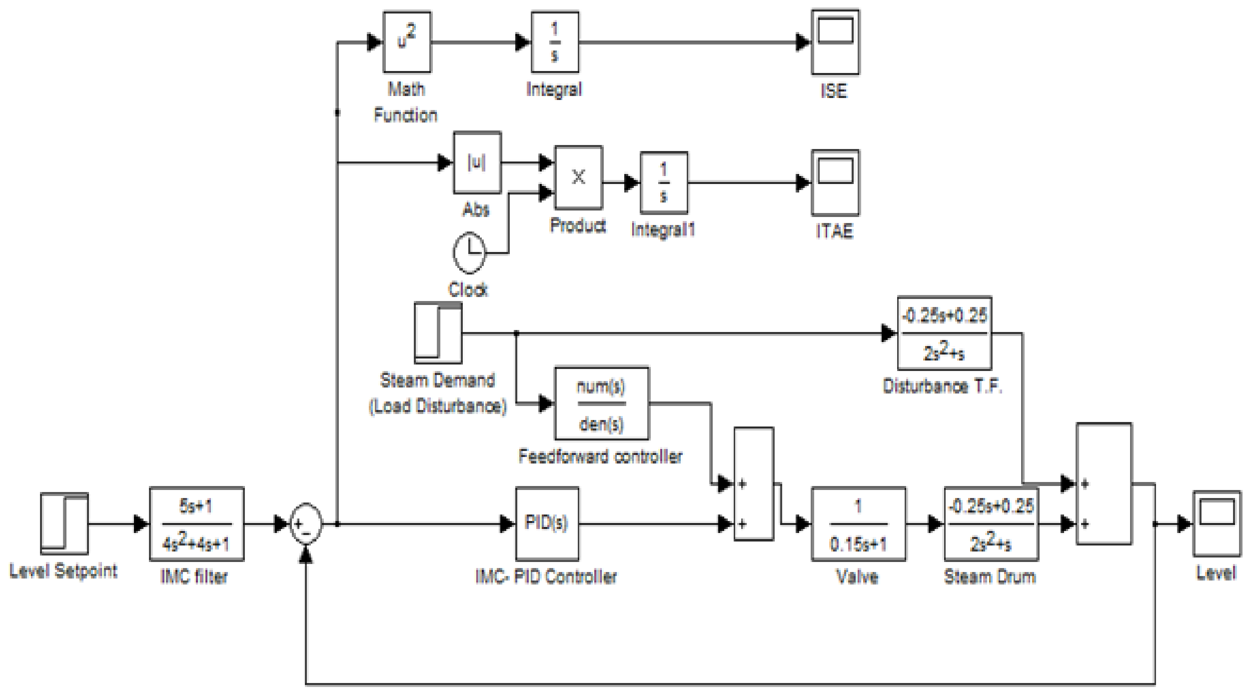

Figure 5.10 Two element drum level control using IMC based PID controller without feed water flow disturbance

5.11 TWO ELEMENT STEAM DRUM LEVEL CONTROL WITHOUT FEEDWATER FLOW DISTURBANCE USING DOUBLE FEEDBACK LOOP METHOD

A double feedback loop along with feed-forward controller is used to enhance the disturbance rejection capability. As the steam load disturbance is introduced into the system, it is necessary to regulate the effect of disturbance by using a feed-forward controller. A double feedback loop gives the better performance and stability of the system comparing to other conventional methods. Figure 5.11 shows the simulink model of two element steam drum level control using double feedback loop method without feed-water flow disturbance. Here feed-water flow disturbance is not considered. The two performance indices ISE and ITAE are also computed.

Unit step block is employed to represent the set point of the system. The internal loop consists of a proportional controller and is tuned by using Ziegler Nichols methodology whereas the external loop controller is tuned by using IMC method.

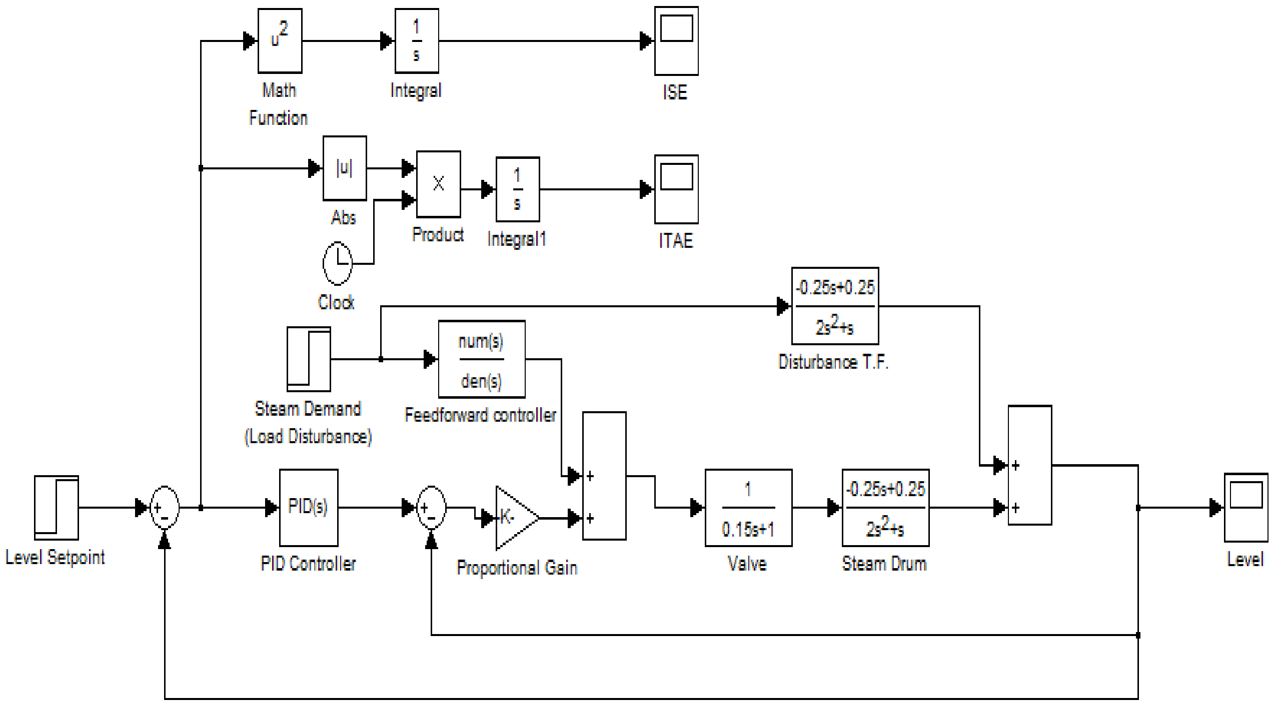

Figure 5.11 Two element drum level control using double feedback loop method without feed water flow disturbance

5.12 COMPARISON OF DIFFERENT CONTROL TECHNIQUES FOR TWO ELEMENT STEAM DRUM LEVEL CONTROL WITHOUT FEEDWATER FLOW DISTURBANCE

Unit step responses of two element boiler drum level control are taken using different control techniques. Here feed water flow disturbance is not considered. Figure 5.12 shows the unit step responses of two element boiler drum level control without feed water flow disturbance using different control techniques. The simulation graph shows the comparison of three different control techniques and it can be seen that response of double feedback loop method has lower overshoot value than PID controller and single loop IMC based PID controller. Also the settling time of double feedback loop method is better than the two methods.

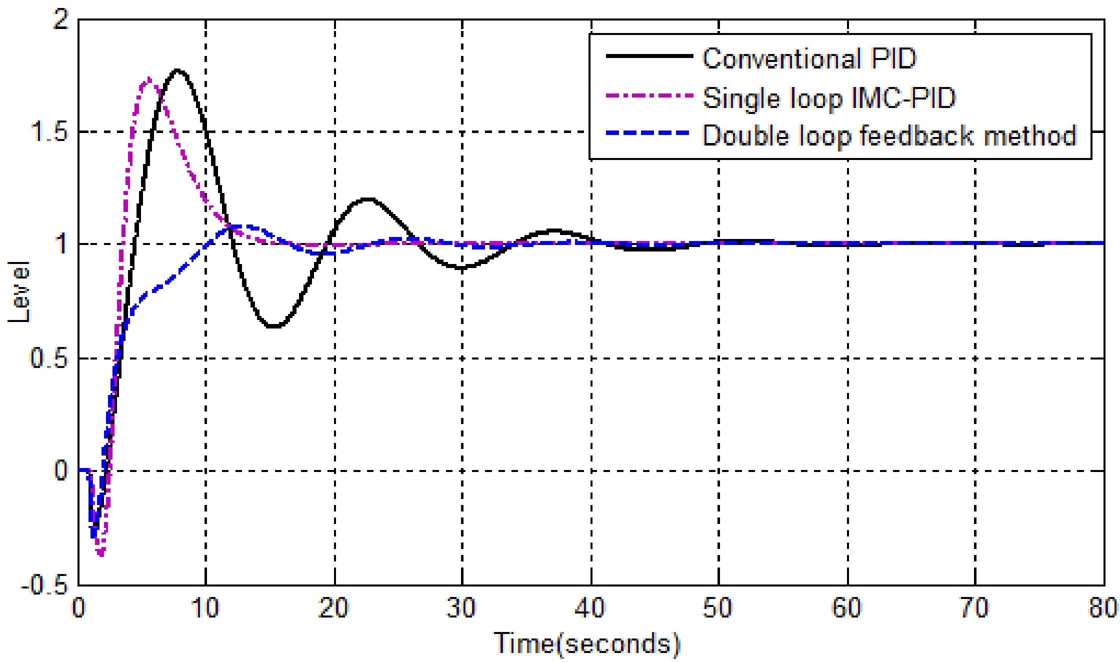

Figure 5.12 Unit Step Response of the two element Steam Drum Level control without feed water flow disturbance

It is determined that the double feedback loop methodology shows better results than both conventional PID controller and IMC based PID controller.

Table 5.3 Comparison of different control schemes using different parameters

TuningMethods / Parameters	PID	IMC-PID	Double Feedback loop method
t_r (sec.)	1.80	1.63	4.2
t_s (sec.)	46.5	15.34	11.75
M_p (%)	76	73	8
ISE	5.4	2.75	2.5
$ITAE$	120	26.5	26

Table 5.3 shows the comparison of different control techniques for two element drum level control without feed water flow disturbance using different parameters including rise time (t_r), settling time (t_s), percentage overshoot (M_p), integral square error (ISE) and integral time absolute error ($ITAE$). It can be seen from Table 5.3 that double feedback loop method has better settling time and percentage overshoot than the conventional methods.

5.13 TWO ELEMENT STEAM DRUM LEVEL CONTROL WITH FEEDWATER FLOW DISTURBANCE USING PID CONTROLLER

The variations in steam drum level can be caused by variations in the flow of feed water. Thus the flow of feed-water acts as the disturbance parameter. The transfer function of feed water flow disturbance is given by [43],

$$G_{d1}(s) = \frac{1}{s} \tag{5.10}$$

Figure 5.13 shows the simulink model of two element control with feed-water flow disturbance using conventional PID controller. Unit step block is used to represent the set point of the system. The two performance indices ISE and ITAE are also computed. Unit step block is taken as the feed water flow disturbance that can vary the water level of steam drum.

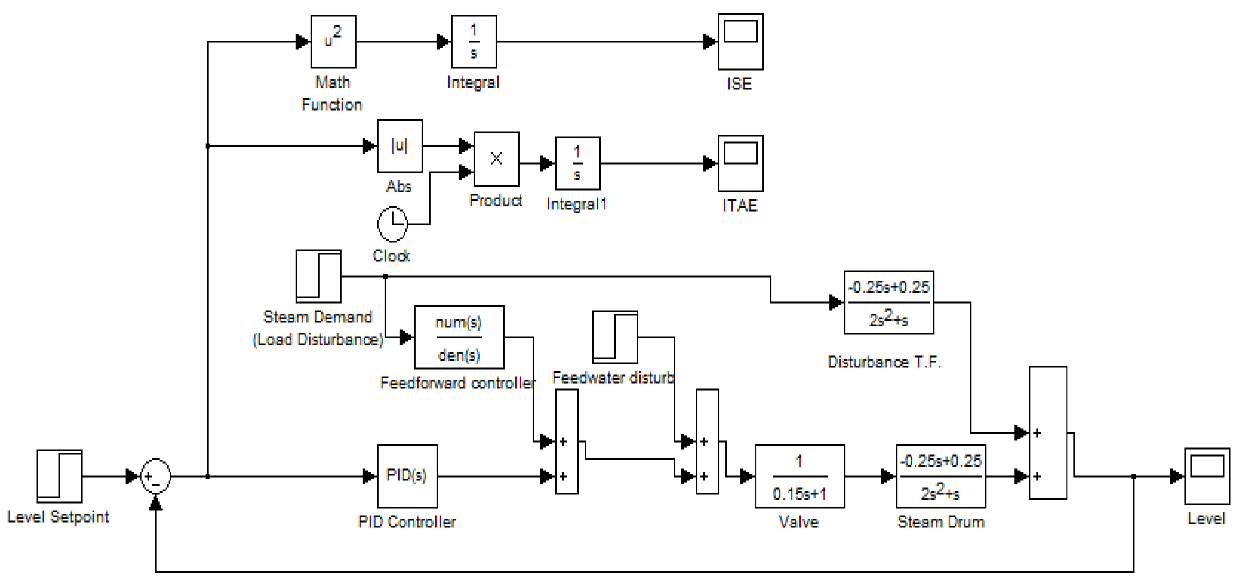

Figure 5.13 Two element drum level control using PID controller with feed water flow disturbance

5.14 TWO ELEMENT STEAM DRUM LEVEL CONTROL WITH FEEDWATER FLOW DISTURBANCE USING IMC-PID CONTROLLER

There can be changes in water level of steam drum due to the variations in flow of feed water. The IMC based PID controller shows finer disturbance rejection capability than conventional PID controller. Unit step input is taken as the feed water flow disturbance.

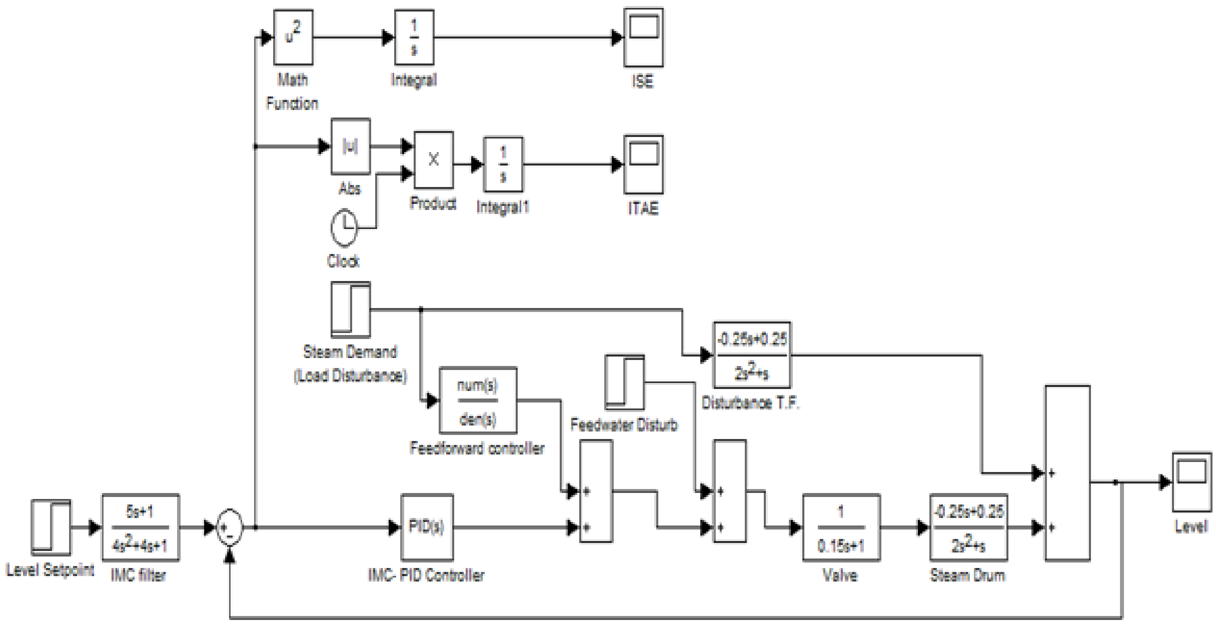

Figure 5.14 Two element drum level control using IMC-PID controller with feed water flow disturbance

Figure 5.14 shows the simulink model of two element level control of steam drum with feed water flow disturbance using IMC-PID controller. Unit step block is used to represent the set point of the system. The two performance indices ISE and ITAE are also computed. Unit step block is taken as the feed water flow disturbance that can vary the water level of steam drum. An IMC based filter is also used in simulink model for the unstable or integrating processes, or for better rejection of disturbance. The steam demand/load disturbance is represented by unit step block.

5.15 TWO ELEMENT STEAM DRUM LEVEL CONTROL WITH FEEDWATER FLOW DISTURBANCE USING DOUBLE FEEDBACK LOOP METHOD

A double feedback loop method is employed to enhance the disturbance rejection capability. As the feed water flow disturbance is introduced into the system, it will affect the water level of steam drum. A double feedback loop gives the better performance and stability of the system comparing to other conventional methods. Figure 5.15 shows the simulink model of two element steam drum level control using double feedback loop method with feed water flow disturbance. Here feed water flow disturbance is considered. The two performance indices ISE and ITAE are also computed. Unit step block represent the input of the system. The internal loop consists of a proportional controller and is tuned by using Ziegler Nichols methodology whereas the external loop controller is tuned by using IMC method.

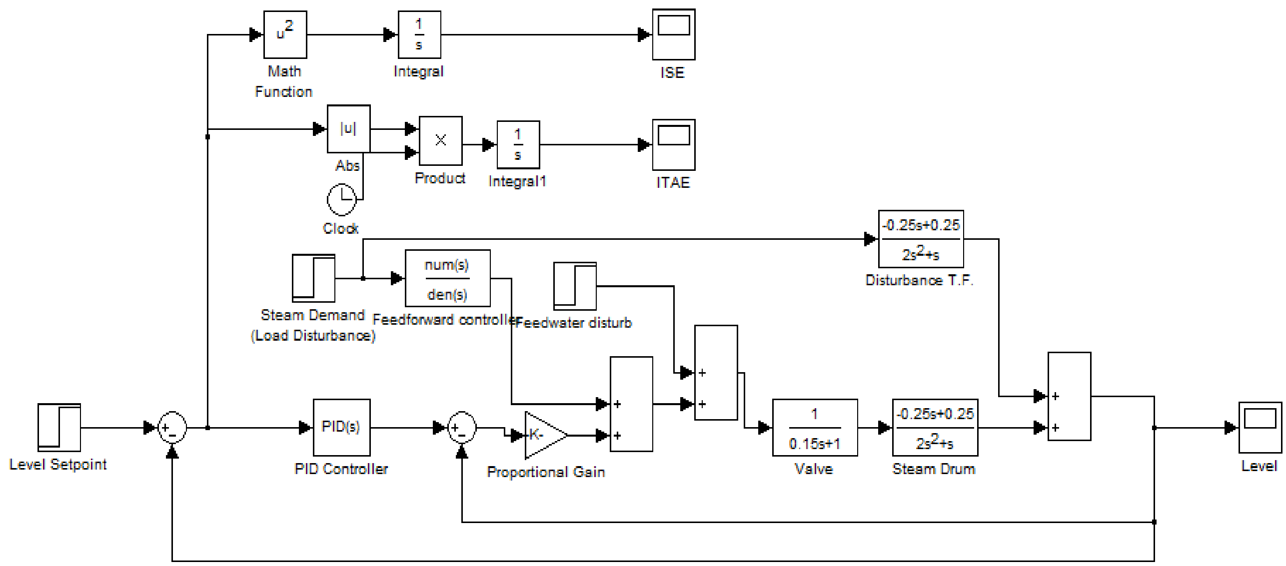

Figure 5.15 Two element drum level control using double feedback loop method with feed water flow disturbance

5.16 COMPARISON OF DIFFERENT CONTROL TECHNIQUES FOR TWO ELEMENT STEAM DRUM LEVEL CONTROL WITH FEEDWATER FLOW DISTURBANCE

Unit step responses of two element boiler drum level control are taken using different control techniques.

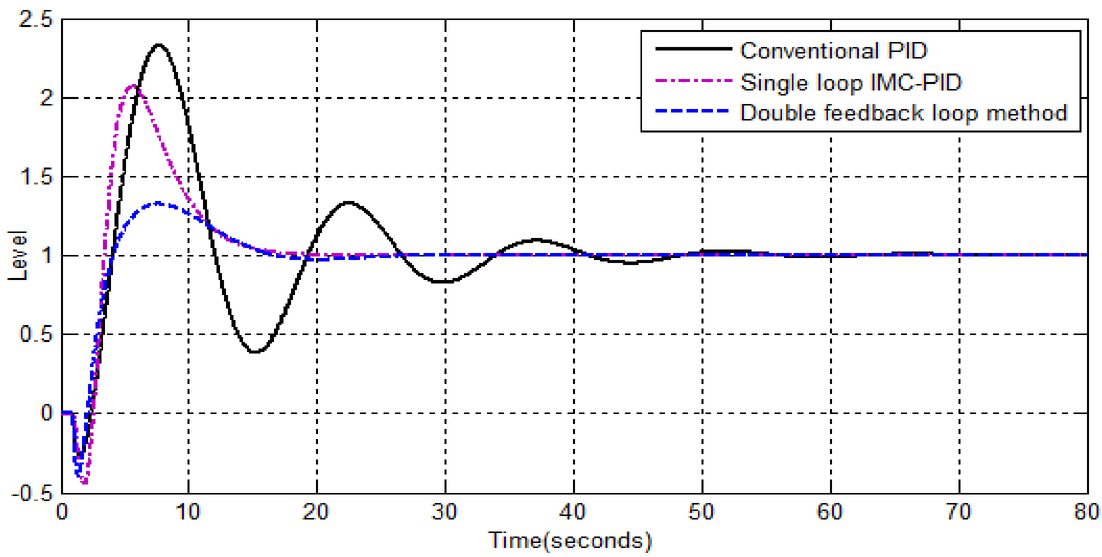

Figure 5.16 Unit Step Response of the two element Steam Drum Level control with feed water flow disturbance

Here feed water flow disturbance is considered. Figure 5.16 shows the unit step responses of two element steam drum level control with feed-water flow disturbance employing different control techniques. It can be seen that the double feedback loop methodology shows better response than both conventional PID controller and IMC-PID controller.

Table 5.4 Comparison of different control schemes using different parameters

Tuning Methods / Parameters	PID	IMC-PID	Double Feedback loop method
t_r (sec.)	1.31	0.681	1.515
t_s (sec.)	47.25	11.5	11.32
M_p (%)	133	107.5	32.4
ISE	11.34	4.55	2.8
$ITAE$	200	37.57	29.3

Table 5.4 shows the comparison of different control techniques for two element drum level control with feed-water flow disturbance using different parameters including rise time (t_r), settling time (t_s), percentage overshoot (M_p), integral square error (ISE) and integral time absolute error ($ITAE$). It is found that double feedback loop method has better settling time and percentage overshoot whereas IMC based PID controller shows better rise time than conventional PID controller.

5.17 THREE ELEMENT STEAM DRUM LEVEL CONTROL USING CONVENTIONAL PID CONTROLLER

The three element drum level control consists of cascade and feed-forward controller. The inner loop controller (slave controller) is a PI controller and is tuned by auto tuning method in simulink while the outer loop controller (master controller) is a conventional PID controller and tuning is done by Ziegler Nichols method.

The parameters of slave controller found out are:

Proportional gain (k_{p2}) =9.094

Integral gain (k_{i2}) =4.425

Transfer function of feed-forward controller is given by,

$$G_{ff}(s) = \frac{-0.699s^3 - 5.3095s^2 - 4.48s - 1}{2s^3 + 5s^2 + 4s + 1} \qquad (5.11)$$

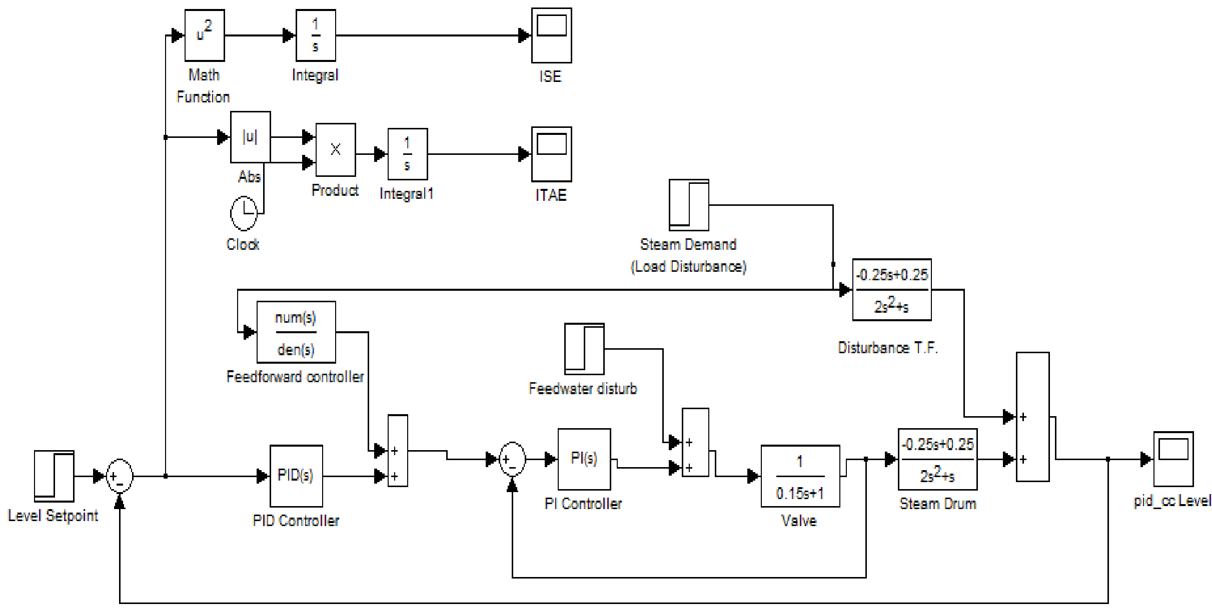

Figure 5.17 Three element steam drum level control using conventional PID controller

The primary controller parameters found out are:

Proportional gain (k_{p1}) =2.3676

Integral gain (k_{i1}) =0.5017

Derivative gain (k_{d1}) =2.791

Figure 5.17 shows the simulink model for three element control using PI controller as secondary controller and PID controller as primary controller.

5.18 THREE ELEMENT STEAM DRUM LEVEL CONTROL USING IMC BASED PID CONTROLLER

The internal loop controller is a PI controller and is tuned by IMC based PI controller. The outer loop controller is an IMC based PID controller.

The parameters of inner loop controller found out are:

Proportional gain (k_{p2}) =0.3

Integral gain (k_{i2}) =2

The outer loop controller parameters found out are:

Proportional gain (k_{p1}) =1.367

Integral gain (k_{i1}) =0.113

Derivative gain (k_{d1}) =2.843

5.19 THREE ELEMENT STEAM DRUM LEVEL CONTROL USING DOUBLE FEEDBACK LOOP METHOD

The internal loop controller is a Proportional controller and is tuned by using Ziegler Nichols method. The outer loop controller is tuned by an IMC based PID method.

The parameters of inner loop controller found out are:

Proportional gain (k_p) =2.12

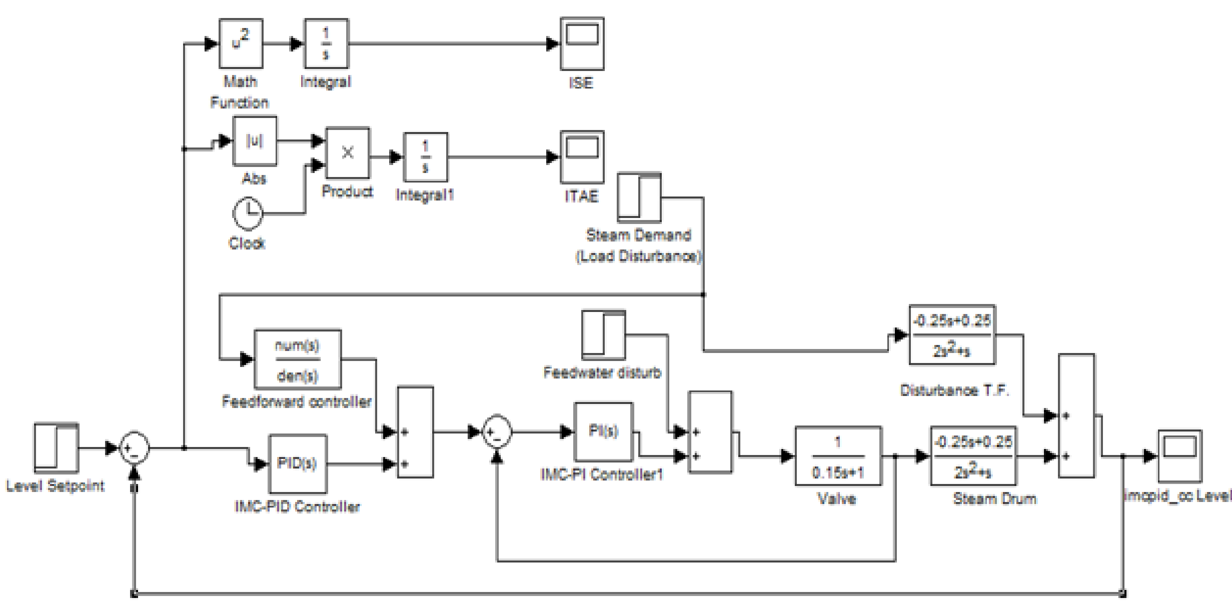

Figure 5.18 Three element steam drum level control using IMC based PID control

The evaluated parameters of external loop controller are:

Proportional gain (k_{p1}) =0.354

Integral gain (k_{i1}) =0.317

Derivative gain (k_{d1}) =1.02

Set point filter (τ_f) =0.35

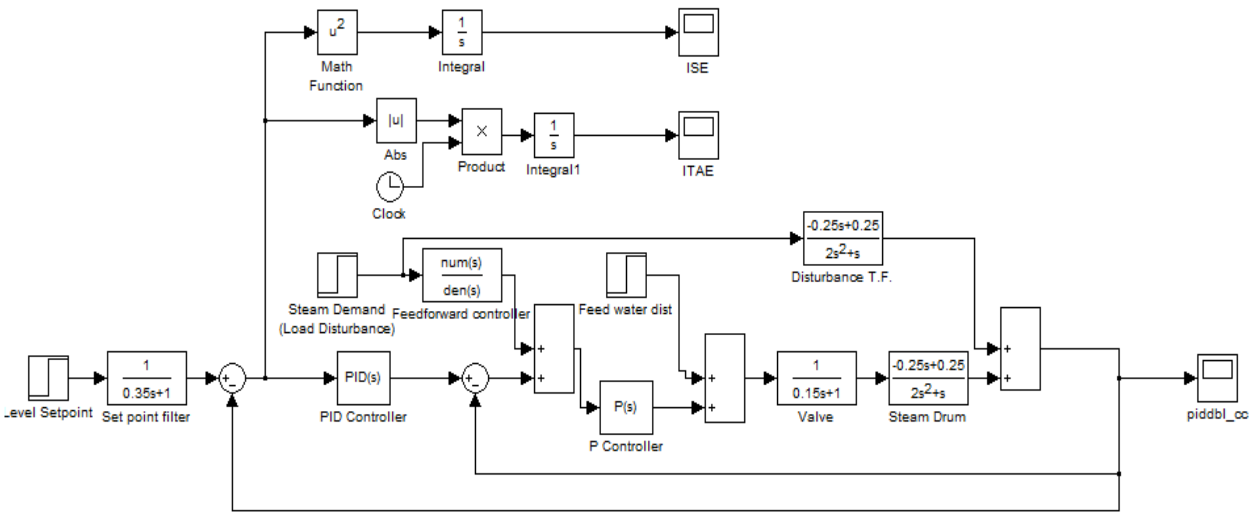

Figure 5.19 Three element steam drum level control using double feedback loop method

Figure 5.19 shows the simulink model for three element steam drum level control using IMC based PID controller in double feedback loop.

5.20 COMPARISON OF DIFFERENT CONTROL TECHNIQUES FOR THREE ELEMENT STEAM DRUM LEVEL CONTROL

Different control techniques are compared including conventional PID controller, single loop IMC based PID controller and double feedback loop method. Figure 5.20 shows the unit step responses of three element drum level control using different control techniques. The simulation graph shows the comparison of three different control techniques and it can be seen that response of double feedback loop method has lower overshoot value than PID controller and single loop IMC based PID controller. Also the settling time of double feedback loop method is better than the two methods.

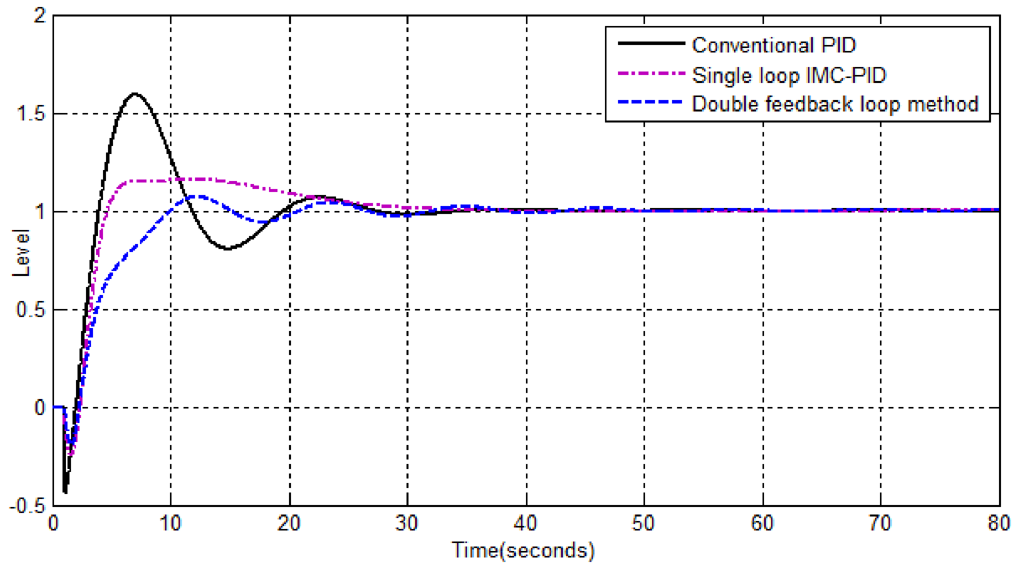

Figure 5.20 Three element drum level control using different control schemes

It can also be seen that the conventional PID controller has better rise time than other two techniques.

Table 5.5 Comparison of different control schemes

Tuning Methods / Parameters	PID	IMC-PID	IMC-PID Double Feedback
t_r (sec.)	1.52	1.70	3.85
t_s (sec.)	31.5	30.84	28.75
M_p (%)	60	15	7
ISE	3.7	2.76	2.26
$ITAE$	53	43.7	38

Table 5.5 shows the comparison between different control techniques for three element drum level control using different parameters including rise time (t_r), settling time (t_s), percentage overshoot (M_p), integral square error (ISE) and integral time absolute error ($ITAE$). It can be seen from Table 5.5 that the double feedback loop method has better results in terms of settling time (t_s), percentage overshoot (M_p), ISE and ITAE.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

The dissertation focuses on the implementation of double feedback loop method to regulate the level of steam drum and also a set point filter is designed to reduce the undesired overshoot introduced into the system due to load/disturbances. The level of steam drum is controlled using different types of drum level control i.e. single element control, two element control and three element control. Also a comparative analysis of different control schemes including conventional PID controller and IMC based PID controller with the double feedback loop method is made.

For **single element control**, simulation results show that the IMC based PID controller gives better response than conventional PID controller in terms of distinct control parameters with rise time improved by 1.27 seconds, settling time by 32.6 seconds, percentage overshoot by 5%, ISE by 34.42% and ITAE by 613.91%. Furthermore, the response of double feedback loop method is better than both conventional and IMC based PID controller. The different control parameters of double feedback loop method are improved as compared to single loop IMC based PID controller with settling time improved by 0.88 seconds with no percentage overshoot. ISE is improved by 97.84% and ITAE by 72.44%. For **second element control**, IMC based PID controller is more effective than conventional PID controller with improvement in rise time by 0.17 seconds, in settling time by 31.16, percentage overshoot by 3%, ISE by 96.36% and ITAE by 352.83%. Further, the performance of double feedback loop method is superior than IMC based PID controller in terms of different control parameters with settling time improved by 3.59 seconds, percentage overshoot by 65%, ISE by 10% and ITAE by 1.92%. For **three element control**, simulation results show that the IMC based PID controller gives better response than conventional PID controller in terms of distinct control parameters with settling time improved by 0.66 seconds, percentage overshoot by 45%, ISE by 34.05% decrease and ITAE by 21.28% decrease. Furthermore, the response of double feedback loop method is better than both conventional and IMC based PID controller. The different control parameters of double feedback loop method are improved as compared to single loop IMC based PID controller with settling time is improved by 2.09 seconds, percentage overshoot by 8%, ISE by 22.12% decrease and ITAE by 15% decrease.

In future, following improvements in this work can be made:

- A fuzzy PID controller can be implemented as a primary control in double feedback loop to improve the control performance.
- Delay can be introduced to analyze the system characteristics.
- Adaptive feed-forward controller can be implemented to reject steam load disturbances.

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