DESIGN OF PID CONTROLLER FOR FOPDT AND IPDT SYSTEM

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENT FOR THE DEGREE OF

Master of Technology (Dual Degree) in Electrical Engineering

By
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2015

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Master of Technology (Dual Degree) in
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Under the Guidance of
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Certificate

This is to certify that the thesis entitled, "**Design of PID controller for FOPDT & IPDT system**" submitted by Mr. Ruben Kandulna in partial fulfilment of the requirements for the award of Master of Technology (Dual degree) degree in Electrical Engineering at the National Institute of Technology, Rourkela, is an authentic work carried out by me under my supervision and guidance.

To the best of my knowledge the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any degree or diploma.

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ABSTRACT

One of the past control procedures is the PID control which is used many industries.
It can be comprehended on the grounds that it is tuneable effectively and the control structure is basic. In the meantime a few tasteful results have been demonstrated utilizing PID control as a part of control system, in mechanical control despite everything it has an has a widespread variety of presentations.

As per a study it has been found that each control area requires PID type for process control systems directed which was studied in 1989. For a long time PID control has been an energetic study subject.

Since numerous process plants have comparable dynamics which is PID controlled and it has been found from less plant data it is possible to set acceptable controller.

In this few controller design techniques is been presented for PID-type, and resulting details for the tuning algorithms is discussed. The PID control are all described fully, and some differences of the classic PID structure are presented.

The perceived experimental Ziegler–Nichols tuning formula and for the PID controller design algorithms approaches have been made for finding the corresponding FOPDT model. Some other simple PID setting formulae such as the Cohen–Coon formula, Chien–Hrones–Reswick formula, Zhuang–Atherton optimum PID controller, Wang–Juang–Chan formula and is presented. Some of the design techniques on PID control is presented, such as Smith predictor design and IMC control design. At long last, a few thoughts on the structure of the controller determinations for process control system are given.

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RUBEN KANDULNA (710EE3147)

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1. INTRODUCTION

1.1 Introduction to Control:

Control designing manages Dynamic structures, for example, cars, flying machine, ships and trains, for example, refining sections and principally in steel moving plants, electrical systems, for example, power system, generators, and motors and numerically controlled machines and robots.

There are some variables which are dependent, called outputs, which is to be controlled, which must be made to act in a recommended manner. Case in point it might be important to appoint the pressure and temperature in a process at different points, or the power system's voltage and frequency, to given desired unchangeable value.

Some variables which are not dependent, called inputs, for example, valve position or voltage connected to the engine terminals, to direct and control the conduct of the system.

There are disturbances influencing which are affecting the system are not known. These could be, for instance load variances in power systems, disturbances influences, for example, wind blows following up on a vehicle, on exposing and cooling plant outside climate conditions is acting, or the load torque fluctuating on a lift engine, as travellers enter and way out.

The parameters contained in these comparisons and the mathematical statements depicting the plant elements, are not no doubt understood at all or, best case scenario known generally. System parameter changes as the set point changes.

The input and output of a plant to be controlled is given as.

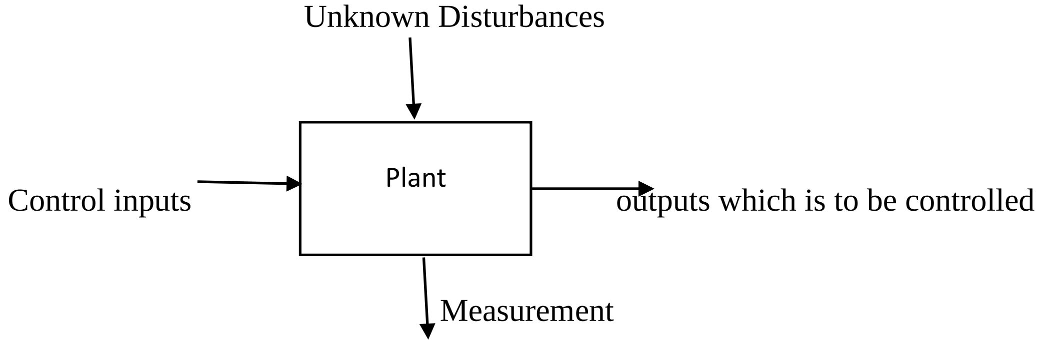

Fig 1.1 Input and output of a plant which is to be controlled

In Fig. 1.1 the outputs or inputs demonstrated can really be speaking to a signal of vectors. Control which is practiced by input, which really implies that the useful input to the plant which is controlled is driven by available estimations which is produced by a device. We can see the control system shown in Fig. 1.2.

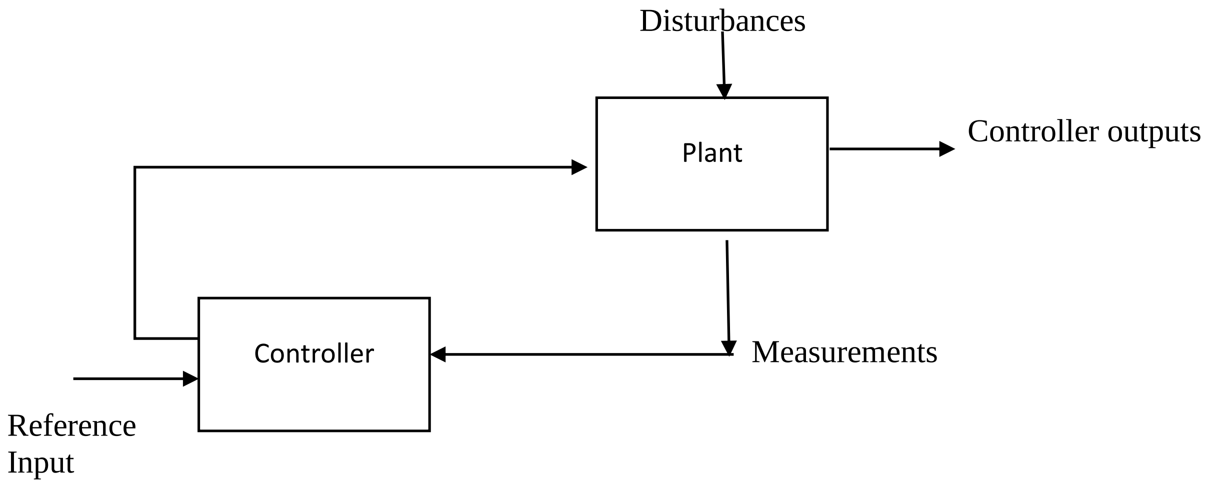

Fig. 1.2. Control system with feedback.

The main purpose of designing the control system so as to meet some criteria so that the output can be

1. Set to a fixed value which is called as reference value;

2. Even though there is some unknown disturbances, reference value should be maintained;

The first one is said to be tracking, the second one is said to be disturbance rejection,. If both the condition are met then the control system design can be a robust servomechanism.

1.2 Closed loop SISO system:

The single-input single-output (SISO) system is the essential control loop and can be simplified as in Fig.1.3 Here the disturbances present in the system are ignored.

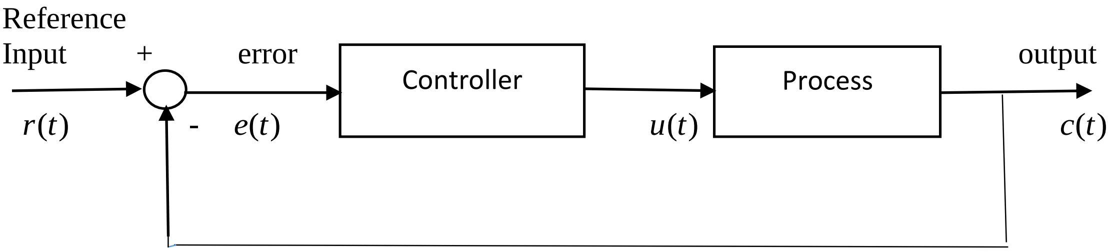

Fig.1.3 A closed loop SISO system

Normally, a controller is essential to process the error signal such that the general system fulfils certain standards. Some of these criteria are:

1. Reduction in effect of disturbance signal.
2. Reduction in steady-state errors.
3. Sensitivity to parameter changes.

The controllers have various structures so with a specific goal to accomplish favoured execution level various design techniques are there for planning the controller. Anyway, Proportional-Integral-derivative (PID) sort controller is the most famous among them. Actually in the modern control application 95% controllers are of Proportional-Integral-Derivative [16]. As output of the Proportional-Integral-Derivative controller u (t) can be stated in terms of e (t), as:

$$u(t) = K_p[e(t) + \tau_d \frac{de(t)}{dt} + \frac{1}{\tau_i}\int_0^t e(\tau)d\tau] \quad (1)$$

Transfer function of the controller is:

$$C(s) = K_p(1 + \frac{1}{\tau_i s} + \tau_d s) \quad (2)$$

The terms of the controller are defined as:

K_p = proportional gain, τ_d = Derivative time, and τ_i = Integral time.

In the subsequent segment we might try to learn the significance of the individual proportional, integral, derivative. For simplicity we consider first-order transfer function in the absence of time delay:

$$P(s) = \frac{K}{1 + \tau s} \quad (3)$$

1.3 Proportional control:

In the closed loop system only P control is considered:

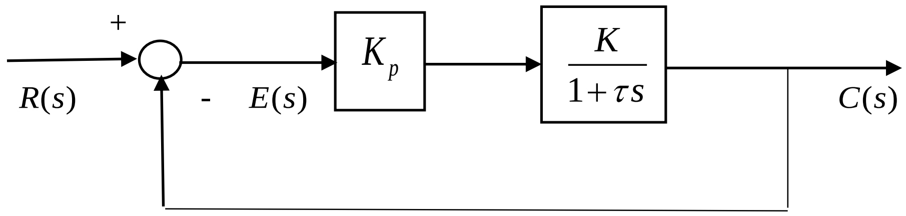

Fig.1.4. Controller with only P

Transfer function is:

$$\frac{C(s)}{R(s)} = \frac{\frac{KK_p}{1+\tau s}}{1 + \frac{KK_p}{1+\tau s}} = \frac{KK_p}{1 + KK_p + \tau s} = \frac{KK_p}{1 + KK_p}\frac{1}{1 + \tau' s} \quad (4)$$

Where $\tau' = \frac{\tau}{1 + KK_p}$

For a step input $R(s) = \frac{A}{s}$

$$R(s) = \frac{KK_p}{1 + KK_p}\frac{A}{s(1 + \tau' s)}$$

Or, $c(t) = \frac{AKK_p}{1 + KK_p}(1 - e^{-s\tau/\tau'})$ (5)

The system response is shown in Fig. 1.5.

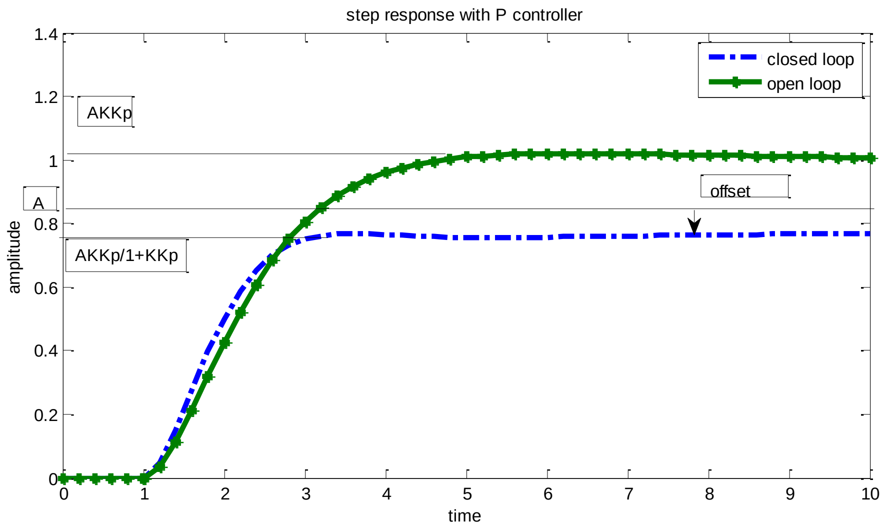

Fig.1.5.Response with a proportional controller

It is apparent from eqn. (5) and Fig. 1.5.

1. By a factor $\dfrac{1}{1+KK_p}$ the time response is enhanced (i.e. the time constant declines).
2. There is a steady state offset between reference and the output =

$$A(1-\frac{KK_p}{1+KK_p})=\frac{A}{1+KK_p}$$

3. By increasing the proportional gain offset can be reduced; however oscillations can increment for systems with higher order. From error transfer function, the steady state error can be obtained and in terms of Laplace transform, the error function e(t) can be represented as:

$$E(s)=\frac{1}{1+\dfrac{KK_p}{1+\tau s}}\frac{A}{s}=\frac{1+\tau s}{1+KK_p+\tau s}\frac{A}{s} \qquad (6)$$

The steady state error can be evaluated by using final value theorem

$$e_{ss}=\lim_{t\to\infty}e(t)=\lim_{s\to 0}sE(s)=\lim_{s\to 0}\frac{1+\tau s}{1+KK_p+\tau s}\frac{A}{s}=\frac{A}{1+KK_p} \qquad (7)$$

Proportional band is defined as the band of error which causes a 100% variation in the controller output expressed as a percentage of range measurement.

1.4 Integral Control:

For closed loop system, the integral control is demonstrated in Fig. 1.6.

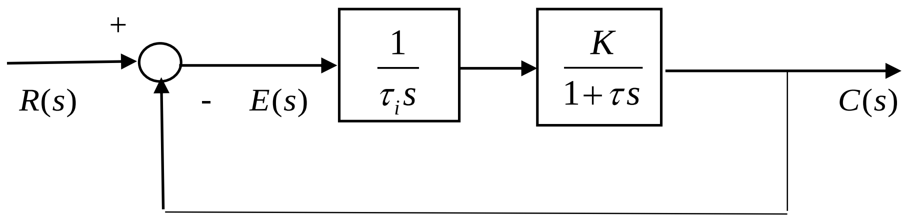

Fig.1.6. Integral Control action

Continuing the same as in eqn. (4),

$$\frac{C(s)}{R(s)}=\frac{\dfrac{K}{\tau_i s(1+\tau s)}}{1+\dfrac{K}{\tau_i(1+\tau s)}}=\frac{K}{K+\tau_i s+\tau\tau_i s^2} \tag{8}$$

We can see from above that closed loop systems order is increased by 1 so, it may cause instability as the process dynamic becomes higher order.

For input step $R(s)=\dfrac{A}{s}$

$$E(s)=\frac{1}{1+\dfrac{K}{\tau_i(1+\tau s)}}\frac{A}{s}=\frac{\tau_i s(1+\tau s)}{\tau_i s(1+\tau s)+K}\frac{A}{s} \tag{9}$$

$$e_{ss}=\lim_{s\to 0} sE(s)=0$$

Due to input step the steady state error decreases to zero, it is the significant advantage of this integral control. Anyhow, all together, the response of the system is slow, oscillatory and unstable. The step response due to integral control is demonstrated in Fig. 1.7.

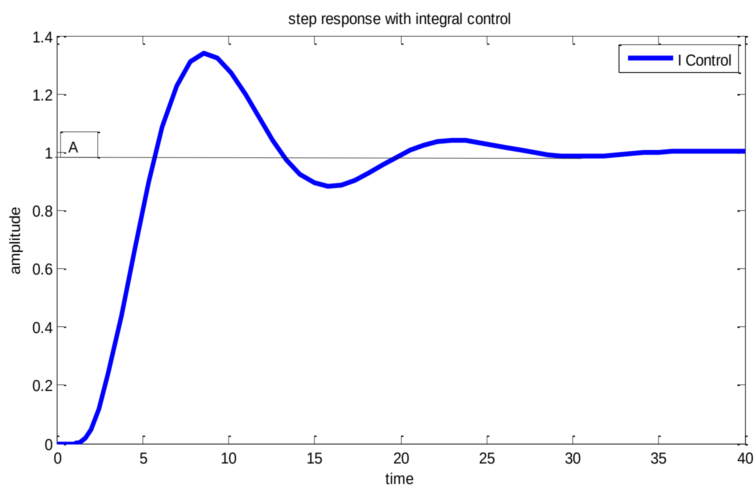

Fig.1.7. Step response with integral control action

1.5 Proportional Plus Integral (P-I) Control:

With Proportional plus integral controller the closed loop system is demonstrated in Fig. 1.8.

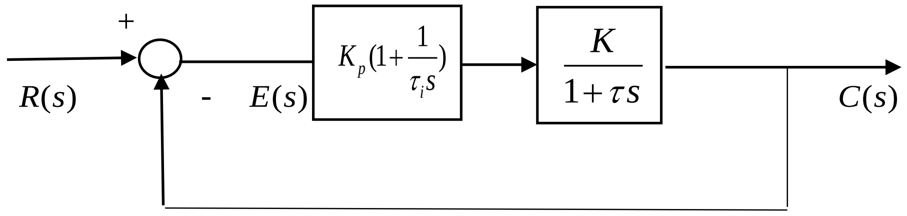

Fig .1.8. Proportional plus Integral Control action

As here we have two control actions P and I, P helps in quick response and I helps in reducing steady state error to zero. The transfer function of the error of the system can be stated as:

$$\frac{E(s)}{R(s)} = \frac{1}{1+\frac{KK_p(1+\tau_i s)}{\tau_i s(1+\tau s)}} = \frac{\tau_i s(1+\tau s)}{s^2\tau\tau_i + (1+KK_p)\tau_i s + KK_p} \tag{10}$$

Additionally, the closed control loop characteristic equation for Proportional-Integral control is

$$s^2\tau\tau_i + (1+KK_p)\tau_i s + KK_p = 0, \tag{11}$$

Damping constant is obtained as:

$$\xi = \left(\frac{1+KK_p}{2}\right)\sqrt{\frac{\tau_i}{KK_p\tau}} \quad . \tag{12}$$

Damping constant for simple integral control is

$$\xi = \left(\frac{1}{2}\right)\sqrt{\frac{\tau_i}{K\tau}}$$

At the point when these two are looked at, one can undoubtedly observe that the damping constant can be increased by changing the term K_p. So we confirm that the steady state error can be zero by utilizing Proportional-Integral control and all together, we see improvement in the transient response. The system output response due to Proportional, Integral and Proportional-Integral control for same plant is thought about from the representation indicated in Fig. 1.9.

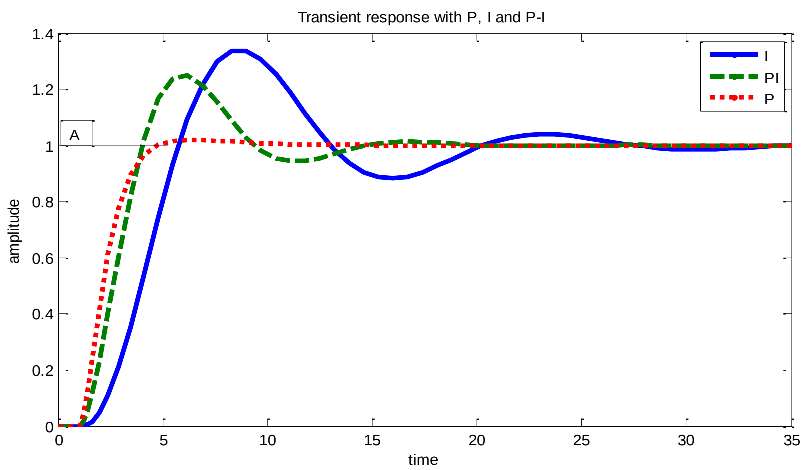

Fig.1.9. Transient response with P, I and P-I

1.6 Proportional plus Derivative (P-D) Control:

Transfer function of P-D controller is given by:

$$C(s) = K_p(1+\tau_d s) \tag{13}$$

P-D control transfer function $P(s) = \dfrac{K}{1+\tau s}$ really is not exceptionally helpful, since it can't decrease the steady state error to zero. But the closed loop system stability can be improved for higher order system using P-D controller. Let $P(s) = \dfrac{1}{Js^2}$ at Fig.8, closed loop transfer function with proportional control is

$$\frac{C(s)}{R(s)} = \frac{\frac{K_p}{Js^2}}{1+\frac{K_p}{Js^2}} = \frac{K_p}{Js^2 + K_p} \tag{14}$$

Characteristics equation is given as $Js^2 + K_p = 0$; response is oscillatory, closed loop transfer function with P-D is:

$$\frac{C(s)}{R(s)} = \frac{\frac{(\tau_d s+1)K_p}{Js^2}}{1+\frac{(\tau_d s+1)K_p}{Js^2}} = \frac{K_p(\tau_d s+1)}{Js^2 + (\tau_d s+1)K_p} \tag{15}$$

Characteristics equation is $Js^2 + K_p(1+\tau_d s) = 0$; that will give a closed loop stable response.

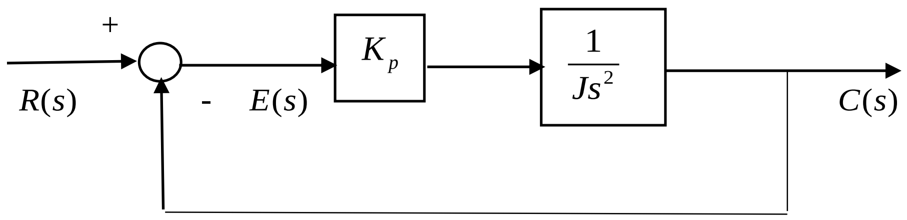

Fig .1.10. Control action with higher order process

1.7 Proportional-Integral-Derivative (PID) control:

It is now clear that the required performance can be obtained by a proper combination of P,I and D action. PID control transfer function is:

$$C(s) = K_p(1+\frac{1}{\tau_i s}+\tau_d s) \tag{16}$$

It is a low order control system, however its applicability is widespread, and it can be utilized as a part of any kind of Single Input Single Output system. A large number of Multiple Input Multiple Output systems are initially subdivided into a few Single Input Single Output loops and for each loop PID controllers are intended. Proportional Integral Derivative controllers have additionally be discovered that it should be robust, and this is the reason why it finds wide suitability for modern procedures. The method of tuning PID parameters would be taken in later chapter.

It is not that necessary that we ought to utilize all the control part. Truth be told, in a large portion of the cases, a basic Proportional-Integral control will be adequate. A broad guidance for the choice of mode of controller to be used, is prescribed [1].

Choice of controller mode:

1. **Proportional Controller**: It is basic for regulation, easy tuning. Anyhow, steady state error is introduced. It is suggested that if the transfer function which is having single dominant pole or having a pole at origin.
2. **Integral Control:** It is relatively slow and no steady state error is observed. It will be operative for quick process, having noise level high.
3. **Proportional-Integral (P-I) Control:** Integral action alone results in faster response. It is widely used for process industries because they do not have large time constants for controlling the variables for example level control, flow control etc.
4. **Proportional-Derivative (P-D) Control:** For larger time constants this P-D controller is used. It has more rapid response and less offset compared to proportional controller. If measurement is noisy one should be careful in using derivative control.
5. **Proportional-Integral-Derivative (P-I-D) Control**: It application is widespread however it's tuning is a touch troublesome. It is mostly helpful for controlling moderate variables, as pH, temperature, and so forth in process industries.

1.8 Motivation & Objective:

The motivation behind this project is to observe different kinds of plant in the real world.
As in the modern day application we come across several control machines and we think of new methods of controlling so, I made a study on different control methods for FOPDT and IPDT plant model.
For FOPDT through Zeigler-Nichols tuning method, the objective was to find the controller parameters to decay the first overshoot to 0.25 times the original overshoot after 1 oscillation.
Chine-Hrones-Reswick tuning method focuses on the main problem consisting of how to regulate set-point and how to reject the disturbances.
Cohen-Coon main approach was to find three dominant poles it should be a pair of complex poles and one real pole such that for load disturbance rejection, the amplitude decay ratio becomes $1/4^{th}$ and the integral error is also minimized. The objective behind this Optimal PID Controller Design methods is to select the Proportional-Integral-Derivative controller parameters which helps in minimizing an integral cost functional. IMC design objective is to minimize the tracking error.
The objective of PDF controller is to result in smooth response to every set-point change and gives maximum robustness whenever there is uncertain parameter.

1.9 LITERATURE REVIEW

The mathematical model of any real time processes can be classified as stable systems, unstable systems and systems with dead time. The PID controller is very important in control engineering application and is widely used in many industries.
An excellent account of many practical aspects of PID control is given in PID Controllers: Theory, Design and Tuning by Astrom and Hagglund [10]. After the study of PID controller, Xu, H., Datta, A., and Bhattcharyya, S. P. [22] explained the study of PID stabilization of linear

time invariant plants with time delay with various tuning methods for different types of plants like FOPDT, IPDT and FOIPDT.
There is a vast mathematical literature on the analysis of stability of time-delay systems which we have not included. We refer the reader to the excellent and comprehensive recent work Stability of Time-Delay Systems by Gu, Kharitonov, and Chen [11] for these results.
The control of time delay systems is still being a challenge to improve its time domain conditions. The survey exposes that the tuning techniques are different for different kind of systems, systems like first order plus dead time delay and others.

The set of tuning rules applicable for the first order plus dead time delay systems are not applicable for IPDT and FOIPDT systems. This means we have to follow different tuning rules for different kind of systems. If there is a parameter variation for any nominal plant, conventional controller are unable to maintain the stability of the system. For this kind of situation we need to design a robust controller where a single controller in able to control the whole plant family. While designing a robust controller we need to keep in mind of its robust stability and performance. Since both the robust stability and performance are inversely proportional to each other, the optimization between these two becomes an interesting one.

There has been several tuning methods empirically proposed, every tuning approach has its own significance, Zeigler-Nichols [20] approach was that after one oscillation, decay the first overshoot to 0.25 times of its original value.
Chine-Hrones-Reswick [19] tuning method focused on how to regulate set-point and how to reject the disturbances. Cohen-Coon [18] tuning method approach was to decay the amplitude ratio for load disturbance so, the load disturbance is rejected also to minimize the integrator error.

Zhuang, M., and Atherton, D. P. [14] also proposed optimal PID controller design method because there approach was to minimize the integral cost function by choosing the PID controller. The controller parameters are determined by minimizing the integral performance criteria such as $ISE, ISTE, IST^2E$. Both the set-point and the load disturbance rejection design specifications are given in this thesis. The obtained results are take on both for tuning purposes and for the evaluation of the performances of an earlier PID controller.

D.E.Rivera, M.Morari and S.Skogestad [17] suggested the IMC design where an internal model is preferred which is basically the original plant whose time delay is been approximated by pade first-order approximation to minimize the tracking error.

Smith predictor control design invented by O.J.M.Smith in 1957, this is a type of predictive controller for pure time delay.

Then other type of plant resulted i.e. integral plus dead time plant who's tuning can't be done by the above procedures so K.G.Arvanitis, G.Syrkos, I.Z.Stellas and N.A.Sigrimis [8] have done some tuning procedures using Pseudo Derivative Feedback controller where integral control is in forward path and the proportional and derivative is in feedback, equations are formed and the parameters for PI and PID are extracted.The objective of PDF controller is to result in smooth response to every set-point change and gives maximum robustness whenever there is uncertain parameter.

IPDT [3]-[6] model has many advantages in the field of tuning, this kind of model has the ability to represent various systems to be controlled by PID controllers. As IPDT contains only two parameters one is gain and the other is time delay therefore it is easy to identify, L.Wang and W.R.Cluett proposed some tuning procedure for IPDT model [21]

For higher order controller its real time implementation becomes difficult in many applications such as aerospace, chemical industries, space vehicles etc. For satisfying some of the robust principles, lower order controller with minimum tuning parameters are presented.

As the structure of the PID controller is fixed our work is to find stable values of proportional gain (K_p), derivative gain (K_d) and the integral gain (K_i) for the first order plus dead time delay plant for set point response and load disturbance rejection and for the integral plus dead time delay for smooth response for every set-point change.
Simulation results obtained for different tuning procedures and analysed and also a smith predictor approach for the system is proposed.

2. PROCESS MODELLING

2.1 PROCESS MODELLING FROM RESPONSE CHARACTERISTICS OF PLANT

In control applications used in industries the plant is modelled as a first-order or second-order system with time delay and the controller is either of the P, PI or the PID type.
From the model it can be seen that this model (23) is helpful for the design of a Proportional-Integral-Derivative control due to the accessibility of a straightforward equation. The technique used in Sec. 2.1.3 for the conclusion to find *L* & *T* of a plant it is easy to use the plot of the step response of the plant. Though in current scenario we need not cut the model up to this form to find apt Proportional-Integral-Derivative parameters of controllers. In this section, successful and regularly utilized calculation is presented.

2.1.1 Transfer function method:

Let us take the first-order plus dead time plant model

$$G(s) = \frac{ke^{-Ls}}{Ts+1}.$$

First-order and second-order derivatives with respect to s,

$$\frac{G'(s)}{G(s)} = -\frac{T}{1+Ts} - L,$$
$$\frac{G''(s)}{G(s)} - \left(\frac{G'(s)}{G(s)}\right)^2 = \frac{T^2}{(Ts+1)^2}. \qquad (17)$$

Evaluating the values at s=0 yields

$$T_{ar} = -\frac{G'(0)}{G(0)} = T + L,$$
$$T^2 = \frac{G''(0)}{G(0)} - T_{ar}^2, \qquad (18)$$

Where T_{ar} = average residence time.

From previous equation, $L = T_{ar} - T$. and from $G(0)$ DC gain value can be evaluated. The key to the FOPDT model is in this way acquired by utilizing the $G(s)$ derivatives in the above formula.

A large selection of plant can be roughly modelled by FOPDT in real time process control system.
Equation of the first-order plus dead time model:

$$G(s) = \frac{K}{Ts+1}e^{-Ls} \qquad (19)$$

Where
K=gain; L= time delay; T= time constant;

We need to find the controller parameters using some of the tuning formulae. Matlab is used to trace the response of plant versus time. Some basic calculation have to be done for finding plant model parameter.

2.1.2 FOPDT (first order plus dead time):

For example, to find the parameters K, L and T by applying a step response to the plant model through an experiment ($a = \frac{KL}{T}$).

Finding parameter of FOPDT:

Process transfer function of a plant is [9]

$$G(s) = \frac{10}{(s+4)(s+3)(s+2)(s+1)} \quad (20)$$

For step response of system matlab code is used and 0.4167 as the steady-state value of (see in Appendix **A.1**).

Step response:

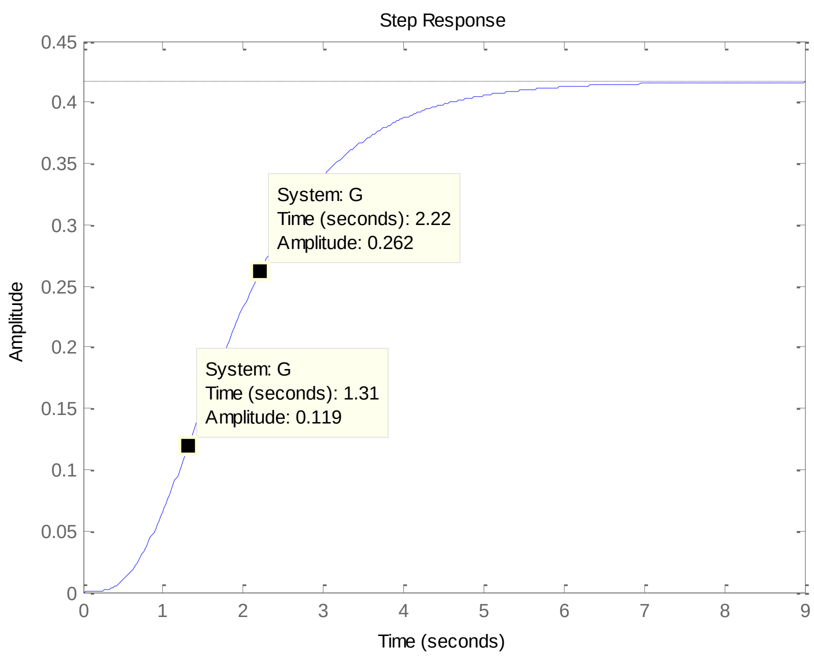

Fig.2.1. step response of process plant

t_1 = the time at gain(c) =0.3 *steady state gain (K)

t_2 = the time at gain(c) = 0.6 *steady state gain (K)

Find T and L

$$T = \frac{3(t_2 - t_1)}{2}$$

L= $(t_2 - t_1)$

$$a = \frac{KL}{T}$$

From step response
K=0.4167
t_1= 1.31 sec
t_2 =2.21 sec
And
L=0.855 sec
T=1.365 sec

We have FOPDT equation as:

$$G(s) = \frac{0.4167}{1.365s + 1} e^{-0.855s}$$

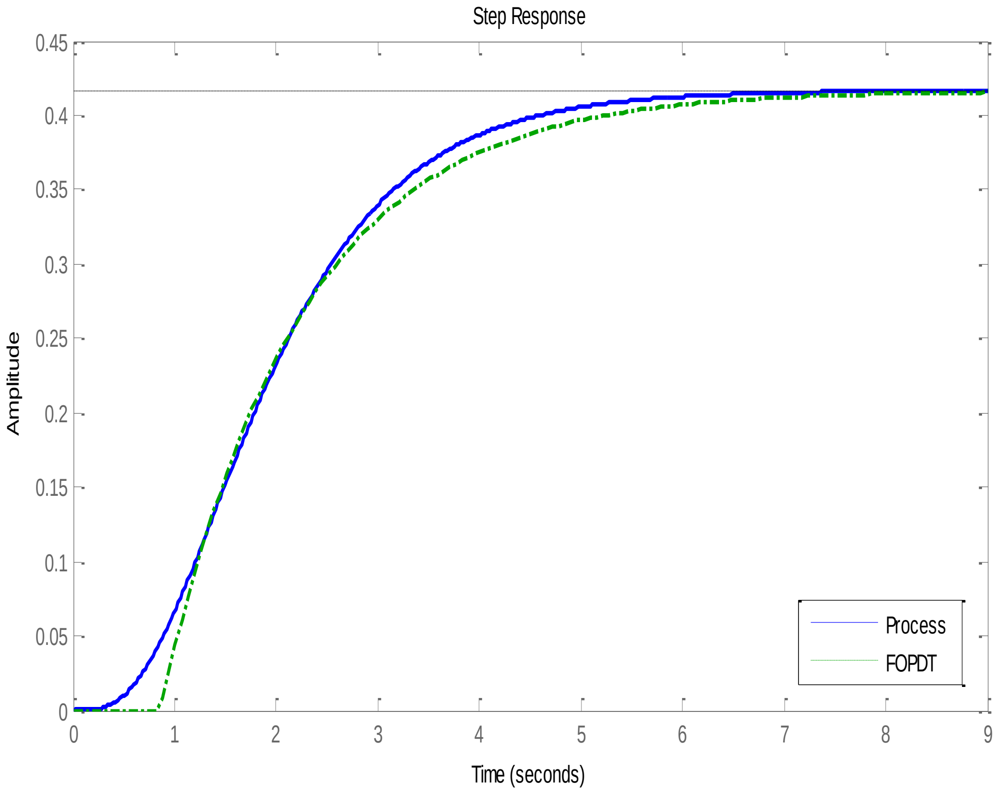

Fig.2.2. step response of Process plant Vs FOPDT

After the modification of process plant transfer function to a FOPDT transfer function it is clear from response that in the FOPDT it shows a clear delay at time of starting. As most of the plant are of accumulated with dead time so this is the reason behind the conversion of the process plant to FOPDT model. It is exciting to note that despite the fact that a large portion of these systems give suitable results, the set of all Proportional-Integral-Derivative controllers for these first-order models with time delay has been explained in the next chapter.

3. DESIGN AND TUNING METHODS

3.1 DIFFERENT TUNING PROCEDURE:

As discussed in the earlier chapter how to model a plant, after modelling we have to control the plant by using PID controller and as PID controller has three parameters we have to find those parameters with the help of some tuning procedures. For finding controller parameters same tuning procedure can't be used for all types of plant model. For each plant model different tuning formula is used.

3.1.1 Ziegler- Nichols method:

The Proportional-Integral-Derivative controller is realised as follows:

$$C(s) = K_p + \frac{K_i}{s} + K_d s$$

Where K_p = proportional gain, K_i = integral gain, and K_d = derivative gain.
In this Ziegler-Nichols it is only valid to open loop plants which are stable [20] as it is an open-loop tuning done by experimentation. In this our prior thing is to find the parameters A and L which we can get it through the plants step response as shown in Fig. 1.8. Firstly we should determine the point where it shows the maximum slope and draw a tangent, this tangent intersects with the vertical axis produces A and intersection with the horizontal axis produces L. By now after we find A and L we can find the Proportional-Integral-Derivative parameters to control.

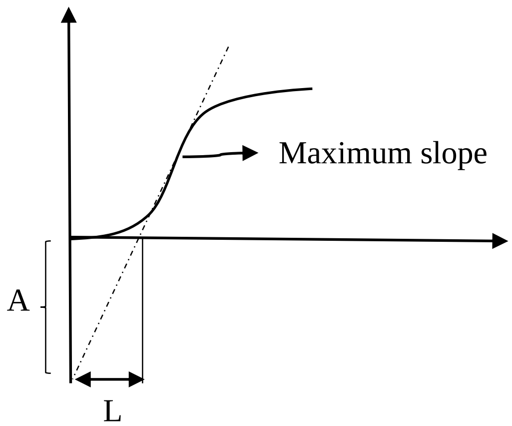

Fig.3.1. plant step response to get A and L.

Empirically obtained formulas are there to produce Proportional-Integral-Derivative control parameters from which we observe that after one oscillation there is a decay in its first overshoot of 0.25 times the original value.

Tuning formula

Controller type	For step response			For frequency response		
	K_p	τ_i	τ_d	K_p	τ_i	τ_d
P	1/a			0.5Kc		
PI	0.9/a	3L		0.4Kc	0.8Tc	
PID	1.2/a	2L	L/2	0.6Kc	0.5Tc	0.12Tc

Here only using step response; controller parameters are found out. Then using Simulink output step response the model plant is taken.
We have FOPDT equation as:

$$G(s)=\frac{0.4167}{1.365s+1}e^{-0.855s}$$

a = 0.19121

P = 5.229

PI = $4.706(1+\frac{1}{2.56s})$

PID = $6.2758+\frac{3.6701}{s}+\frac{2.683N}{1+N/s}$

3.1.2 Chine-Hrones-Reswick tuning:

This method focus on the main problem consisting of how to regulate set-point and how to reject the disturbances. Also regarding speed of response and overshoot an additional comment comparable with the Ziegler–Nichols tuning formula, the time constant T is been used clearly in this CHR method [19].

Closed-loop response which is more heavily damped, guarantees for an ideal plant and the one which is having high response speed without overshoot is considered as overshoot of 0% and other with good response speed with 20% overshoot is considered as overshoot of 20%.

Set point regulation

Controller type	Overshoot of 0%			Overshoot of 20%		
	K_p	τ_i	τ_d	K_p	τ_i	τ_d
P	0.3/a			0.7/a		
PI	0.35/a	1.2T		0.6/a	T	
PID	0.6/a	T	0.5L	0.95/a	1.4T	0.47L

Disturbance rejection

Controller type	Overshoot of 0%			Overshoot of 20%		
	K_p	τ_i	τ_d	K_p	τ_i	τ_d
P	0.3/a			0.7/a		
PI	0.6/a	4L		0.7/a	2.3L	
PID	0.95/a	2.4L	0.42L	1.2/a	2L	0.42L

Table 1. Set point regulation for Chine-Hrones-Reswick:

Controller type	Overshoot of 0%			Overshoot of 20%		
	K_p	τ_i	τ_d	K_p	τ_i	τ_d
P	1.57			3.67		
PI	1.1749	0.99		3.14	1.37	
PID	3.14	1.37	0.43	4.97	1.91	0.402

Table 2. Disturbance rejection for Chine-Hrones-Reswick:

Controller type	Overshoot of 0%			Overshoot of 20%		
	K_p	τ_i	τ_d	K_p	τ_i	τ_d
P	1.569			3.66		
PI	3.14	3.42		3.66	1.96	
PID	4.97	2.052	0.36	6.27	1.71	0.36

3.1.3 Cohen-Coon Tuning algorithm:

Cohen-Coon method [18] is a dominant pole design method and tries to locate some poles to attain definite performance control. The. It is based on first –order plus dead time model:

$$G(s) = \frac{K}{Ts+1} e^{-Ls}$$

This tuning method approach was to decay the amplitude ratio for load disturbance so, the load disturbance is rejected also to minimize the integrator error. This gives good load disturbance rejection, Proportional-Integral-Derivative parameters in relation to K, T, and L:

$$a = \frac{KL}{T}, \ \tau = \frac{L}{L+T}$$

Controller type	K_p	τ_i	τ_d
P	$\frac{1}{a}(1 + \frac{0.35\tau}{1-\tau})$		
PI	$\frac{0.9}{a}(1 + \frac{0.92\tau}{1-\tau})$	$\frac{3.3 - 3\tau}{1 + 1.2\tau}L$	
PD	$\frac{1.24}{a}(1 + \frac{0.13\tau}{1-\tau})$		$\frac{0.27 - 0.36\tau}{1 - 0.87\tau}L$
PID	$\frac{1.35}{a}(1 + \frac{0.18\tau}{1-\tau})$	$\frac{2.5 - 2\tau}{1 - 0.39\tau}L$	$\frac{0.37 - 0.37\tau}{1 - 0.81\tau}L$

Table 3. Cohen-Coon parameters for P, PI, PD, PID

Controller type	K_p	τ_i	τ_d
P	6.3746		
PI	7.416	1.245	
PD	7.019		1.687
PID	7.865	1.74	0.2757

3.1.4. Wang-Juang-Chan method of tuning:

Name itself says that this tuning method is suggested by Wang, Juang, and Chan [9]. For choosing the Proportional-Integral-Derivative control parameters it is an easy & effective method which is built on the optimum Integral-Time-Absolute-Error criterion. The controller parameters can give by, if the parameters K, L & T of the plant are known

$$K_p = \frac{(0.73 + 0.53T/L)(T + L/2)}{K(T+L)} \tag{21}$$

$$\tau_i = T + \frac{L}{2}$$

$$\tau_d = \frac{\frac{L}{2}T}{T + \frac{L}{2}}$$

$K_p = 3.0568, \tau_i = 1.7925, \tau_d = 0.3255$

3.1.5 Optimal PID Controller Design [14]:

This method tries to find the PID parameters which minimizes the integral cost function.

$$J_n(\theta) = \int_0^{\infty} [t^n e^2(\theta, t)]dt \qquad (22)$$

Where θ = vector having the parameters of the controller and e (θ, *t)* signifies the signal error. Another influence is due to Pessen [13], who utilized IAE principle:

$$J(\theta) = \int_0^{\infty} |e(\theta, t)| dt \qquad (23)$$

To represent time function in Laplace transform we make use of Parseval's Theorem to minimize the cost function [12]. To minimize the integral cost function as soon as the integration gets started, the Proportional-Integral-Derivative controller parameters are adjusted.

Set-Point optimum PID tuning:

For PI controller:

$$K_p = \frac{a_1}{k}(\frac{L}{T})^{b_1}, \tau_i = \frac{T}{a_2 + b_2(L/T)} \qquad (24)$$

For PID controller:

$$K_p = \frac{a_1}{k}(\frac{L}{T})^{b_1}, \tau_i = \frac{T}{a_2 + b_2(L/T)}, \tau_d = a_3 T(\frac{L}{T})^{b_3} \qquad (25)$$

The values for a_1, b_1, a_2, b_2 for set point regulation for all the controller types their paramters depending upon the range of L/T is given in[9].

Disturbance rejection PID controller:

PI controller:

$$K_p = \frac{a_1}{k}(\frac{L}{T})^{b_1}, \tau_i = \frac{T}{a_2}(\frac{L}{T})^{b_2} \qquad (26)$$

Proportional-Integral-Derivative controller:

$$K_p = \frac{a_1}{k}(\frac{L}{T})^{b_1}, \tau_i = \frac{T}{a_2}(\frac{L}{T})^{b_2}, \tau_d = a_3 T(\frac{L}{T})^{b_3} \qquad (27)$$

The values for a_1, b_1, a_2, b_2 for disturbance rejection for PI and PID controller paramters depending upon the range of L/T is given in[9]

Controller parameter on the basis of this tuning:

Table 4. For set point tracking PI Controller**:**

Criterion	K_p	τ_i	τ_d
ISE	3.5696	2.3022	
ISTE	2.629	1.678	
IST^2E	2.1306	1.498	

Table 5. For set point tracking PID Controller

Criterion	K_p	τ_i	τ_d
ISE	3.826	1.415	0.4406
ISTE	3.8044	1.629	0.3116
IST^2E	3.546	1.668	0.3404

Table 6. For set point tracking with D in feedback path using PID controller:

Criterion	K_p	τ_i	τ_d
ISE	4.579	2.2417	0.3382
ISTE	3.904	2.0744	0.3117
IST^2E	3.498	1.982	0.276

Table 7. For disturbance rejection using PI Controller:

Criterion	K_p	τ_i	τ_d
ISE	1.458	1.946	
ISTE	1.1635	1.581	
IST^2E	1.1682	1.681	

Table 8. For disturbance rejection using PID Controller:

Criterion	K_p	τ_i	τ_d
ISE	1.693	0.8607	0.482
ISTE	1.693	1.0322	0.389
IST^2E	1.757	0.992	0.364

3.1.6 Smith Predictor design

Using the above parameters for K_p and K_i;

The first-order plus dead time with a 1.365 second time constant and 0.855 second time delay. The Smith Predictor control structure is

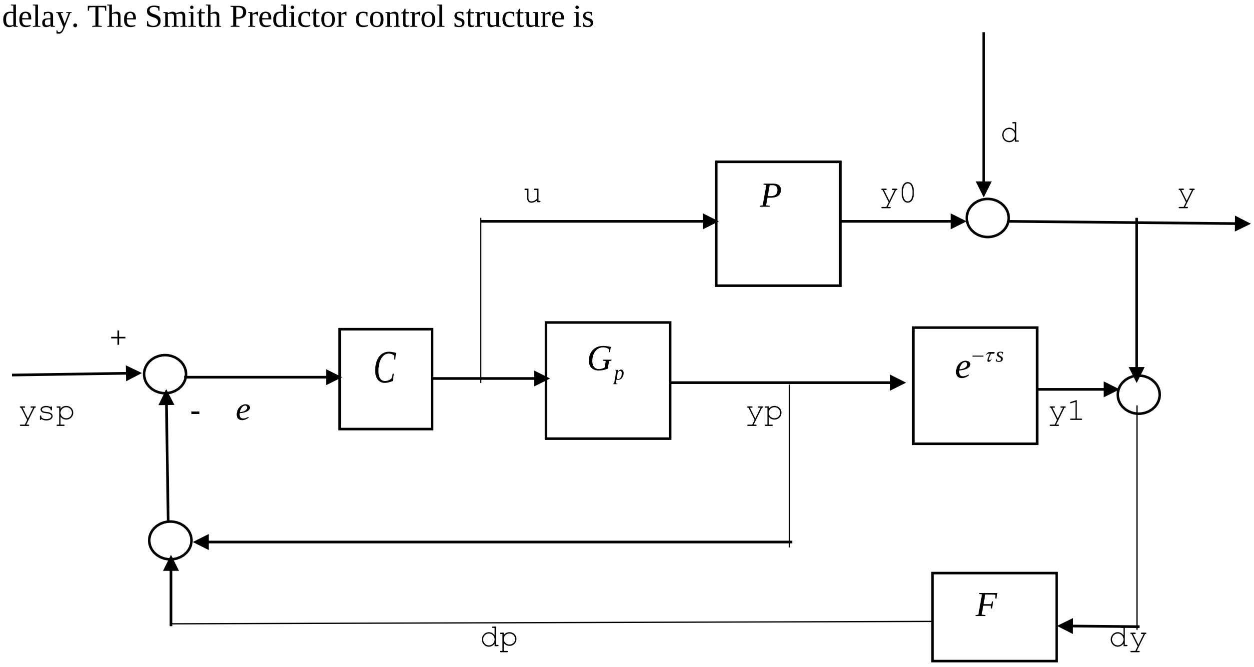

Fig.3.2. Smith Predictor structure

By using the matlab code (see in Appendix **A.2**):

The step response of the first-order plus dead time plant is

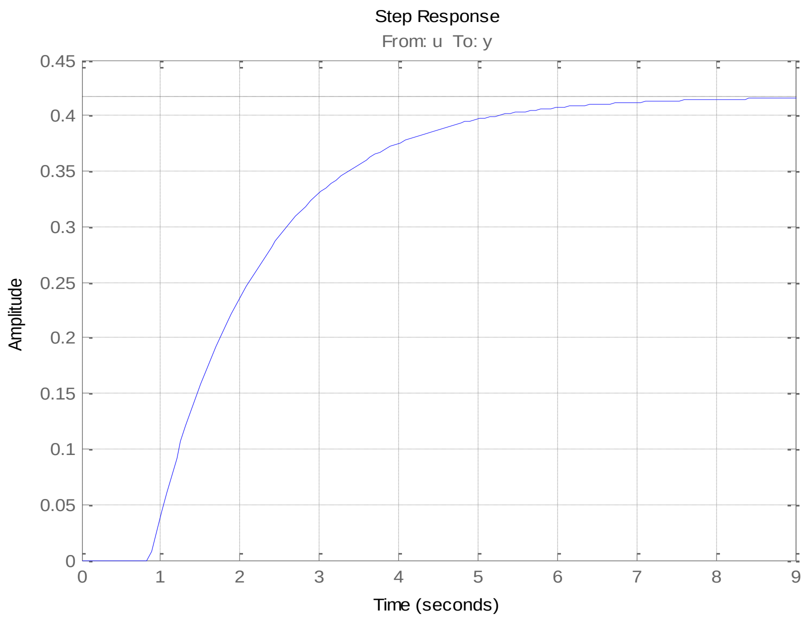

Fig. 3.3. Step response of FOPDT plant

PI Controller:

In process control Proportional-Integral (PI) control is a commonly used technique. The PI control standard diagram is shown in fig.6.3.

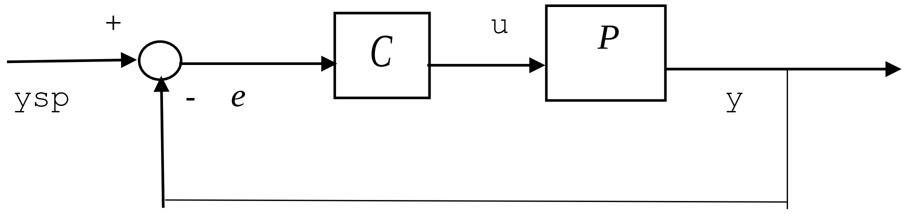

Fig.3.4. Basic PI control structure

C is a compensator with two tuning parameters proportional gain K_p and an integral time τ_i.

Here we have taken K_p and τ_i values from Chine-Hrones-Reswick PID tuning algorithm for 0% overshoot.

With $K_p = 1.17$, $K_i = 1.18$

The feedback loop is closed and it is been simulated to observe the responses to the step change in the reference signal `ysp` and output disturbance signal `d` by which we can evaluate PI controller performance.

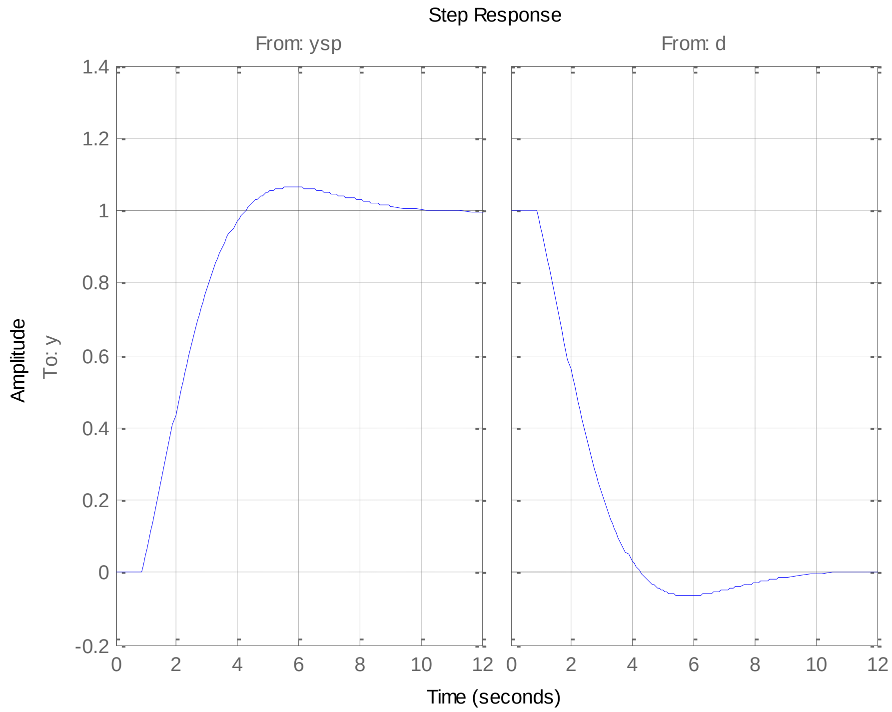

Fig.3.5. Step response of `ysp` and `d`

The closed-loop response has tolerable overshoot but is somewhat slow (it settles in about 12 seconds). To increase the speed of the response we should start increasing the gain K_p but because of this it can lead to instability.

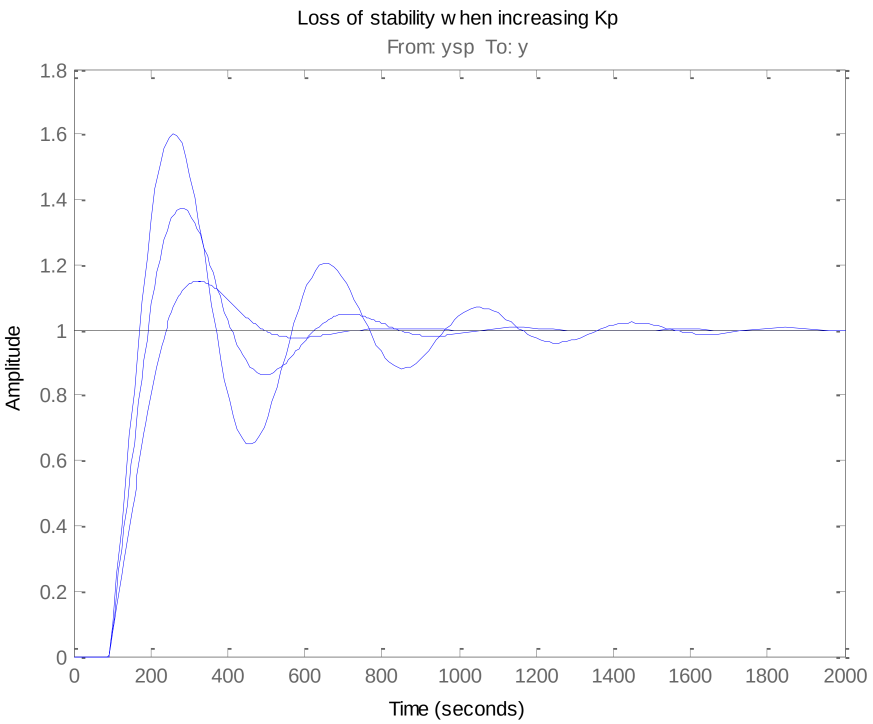

Fig.3.6. loss of stability when K_p increases

Because of the dead time, PI controller performance is not up to the mark because the actual output `y` is not getting matched with the reference set point `ysp`.

The Smith Predictor procedures an internal model G_p to guess the response which is delay-free `yp` of the process. Before it matches this prediction `yp` with the reference set point `ysp` to decide what tunings are needed (control u). By taking in consideration of rejecting their disturbances which are external, the Smith predictor also relates the actual output of the process with a prediction `y1` which takes the dead time into justification. The gap `dy=y-y1` is fed back via a filter F and contributes the error signal e.

Smith Predictor requirements:

A model G_p which is the process and an estimate tau of the process dead time satisfactory settings for the compensator and filter dynamics (C and F)

Based on the process model, we use:

$$G(s) = \frac{0.4167}{1.365s+1} e^{-0.855s}$$

For F, to capture low frequency disturbances we use a first-order filter with a 20 second time constant.

$$F = \frac{1}{20s+1}$$

For C, we re-design the PI controller with the overall plant seen by the PI controller, which includes dynamics from P, G_p , F and dead time. With the help of the Smith Predictor control structure we are able to increase the open-loop bandwidth to achieve faster response and increase the phase margin to reduce the overshoot.

Process

$$P = \frac{0.4167}{1.365s+1} e^{-0.855s};$$

Model predicted

$$G_p = \frac{0.4167}{1.365s+1}$$

$$D_p = e^{-0.855s}$$

Design PI controller with 0.08 rad/s bandwidth and 90 degrees phase margin

Comparison of PI Controller vs. Smith Predictor:
To equate two designs, first derive the transfer function of the closed-loop from `ysp,d` to `y` for the Smith Predictor architecture. To facilitate the task of connecting all the blocks involved, name all their input and output channels and let connect do the wiring:

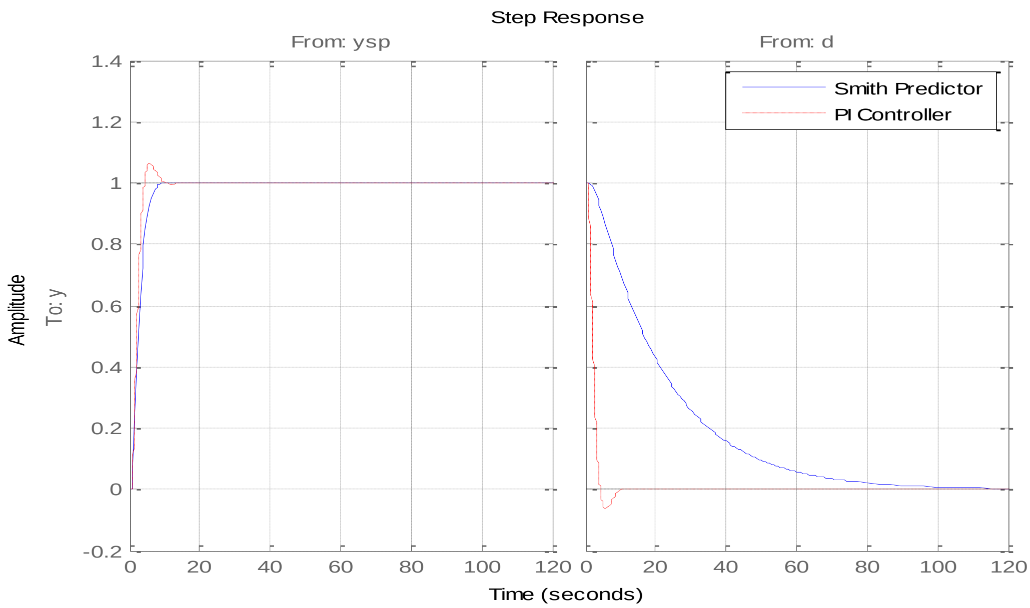

Fig.3.7.Comparison of step response for smith predictor and PI controller

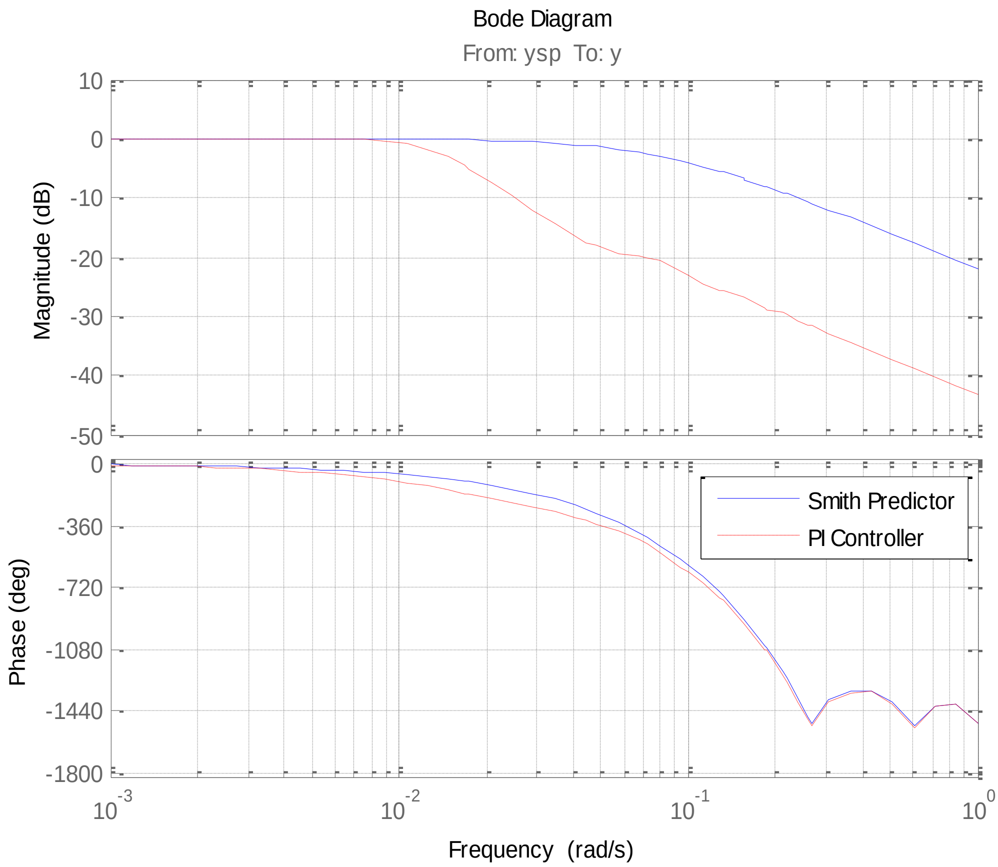

Fig.3.8.Comparison of bode plot for smith predictor and PI controller.

3.1.7 IMC Design:

In process control application IMC design has become famous [17]. In this G(s) is FOPDT, in IMC it is suitable for open-loop stable control systems. The Internal model control consists of a stable internal model controller parameter Q(s) and $\hat{G}(s)$ is the model of the plant. F(s) is internal model controller filter selected to make Q(s) F(s) proper by improving the robustness.

$$C(s) = \frac{F(s)Q(s)}{1 - F(s)Q(s)\hat{G}(s)}. \tag{28}$$

IMC design main objective was to select Q(s) which helps in minimizing the tracking error r-y.

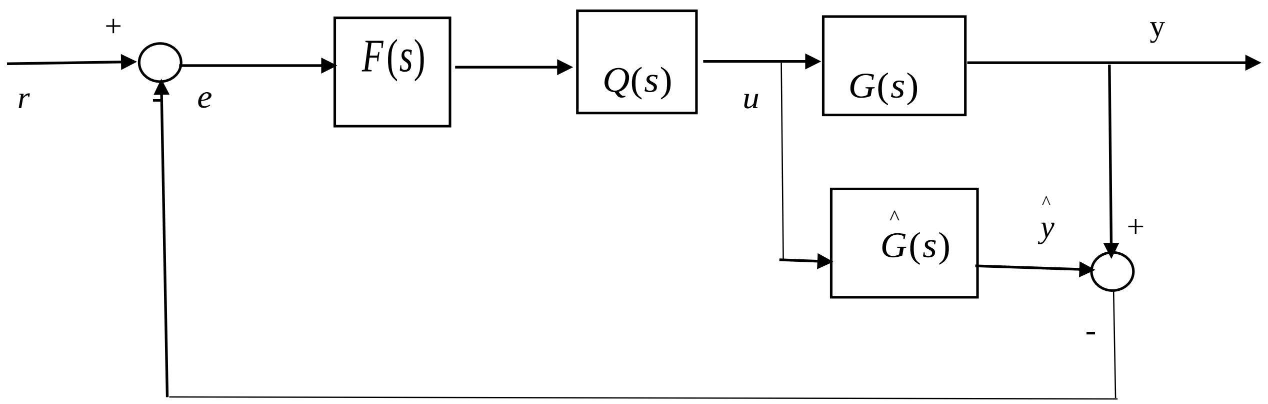

Fig.3.8. IMC configuration.

The following plant is to be controlled:

$$G(s) = \frac{0.4167}{1.365s + 1} e^{-0.855s} \tag{29}$$

By Pade approximation,

$$e^{-0.855s} \approx \frac{1 - 0.4275s}{1 + 0.4275s} \tag{30}$$

$\hat{G}(s)$ Which is the internal model whose transfer function is

$$\hat{G}(s) = \frac{-0.1781s + 0.4167}{0.5835s^2 + 1.7925s + 1} \tag{31}$$

$$Q(s) = \frac{1.365s + 1}{0.4167} \tag{32}$$

Since Q(s) is improper and to get the suitable we have to negotiate between robustness and performance. Zafiriou & Morari [15] have suggested an apt choice to select λ , λ >0.2T and λ >0.25L.

$$F(s) = \frac{1}{1 + 0.274s} \tag{33}$$

The equivalent feedback controller becomes

$$C(s) \cong \frac{(1+Ts)(1+\frac{L}{2}s)}{Ks(L+\lambda)} \tag{34}$$

From the above equation we get the parameters for a standard PID controller:

K_p =3.8101

K_i = 2.1256

K_d = 1.2403

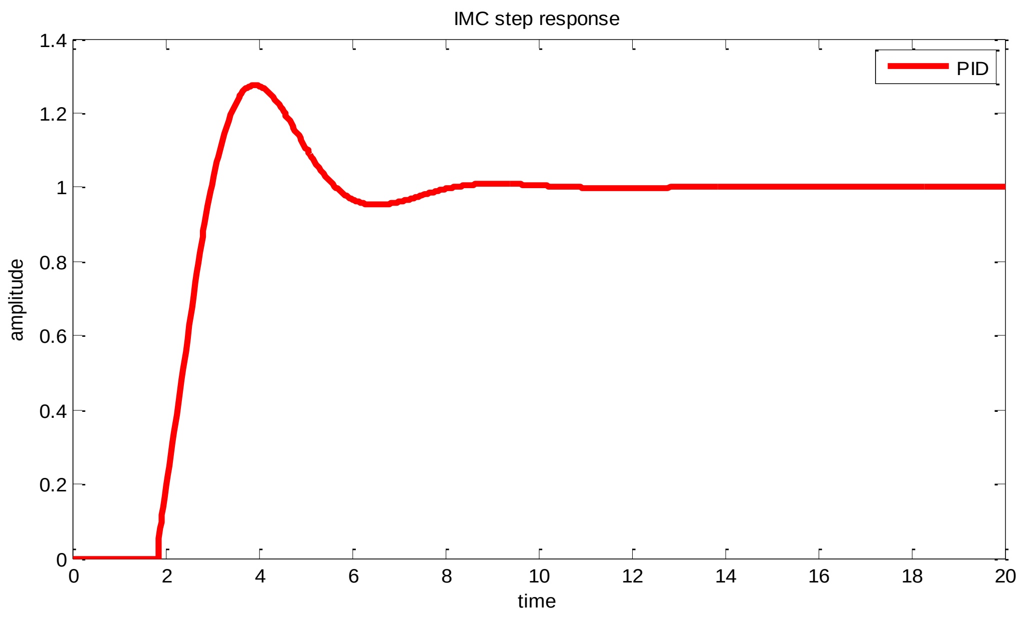

Fig.3.9.step response of IMC

3.1.8 Integrator plus dead time (IPDT) Model:

A generally faced plant which is modelled mathematically $G(s) = \frac{K}{s} e^{-ds}$ is denoted as the IPDT model. IPDT plant cannot be tuned by the earlier tuning procedures. As there is already an integrator so no need of another integrator to remove a steady state error for a step input.

The following IPDT model is experimentally obtained transfer function of a temperature process rig, by controlling the temperature at a particular junction using PID setting in the controller we obtained an input and output data in excel file. Using the input-output data with the help of matlab system identification we obtained this transfer function.

$$G(s) = \frac{0.00017}{s} e^{-20.37s} \tag{35}$$

To control integrating plus dead-time model we should use Pseudo-Derivative Feedback (PDF) structure. The methods used for tuning this PDF structure is simple and results in smooth response to every set-point change and gives maximum robustness whenever there is uncertain parameter.

IPDT [3]-[6] model has many advantages in the field of tuning, this kind of model has the ability to represent various systems to be controlled by PID controllers. As IPDT contains only two parameters one is gain and the other is time delay therefore it is easy to identify.

If the systems having large time constants over critical range of frequency that is near ultimate frequency, IPDT model can be approximated. As we are going on saying that IPDT model is simple but there is less number of tuning approaches compared to FOPDT model. The Ziegler-Nichols methods leads to oscillation and becomes unstable even there is a small perturbations in the parameters of the model.

IPDT model tuning based on the coefficients matching of the powers of ‘s’ in numerator and denominator is discussed in [7], to avoid overshoot.

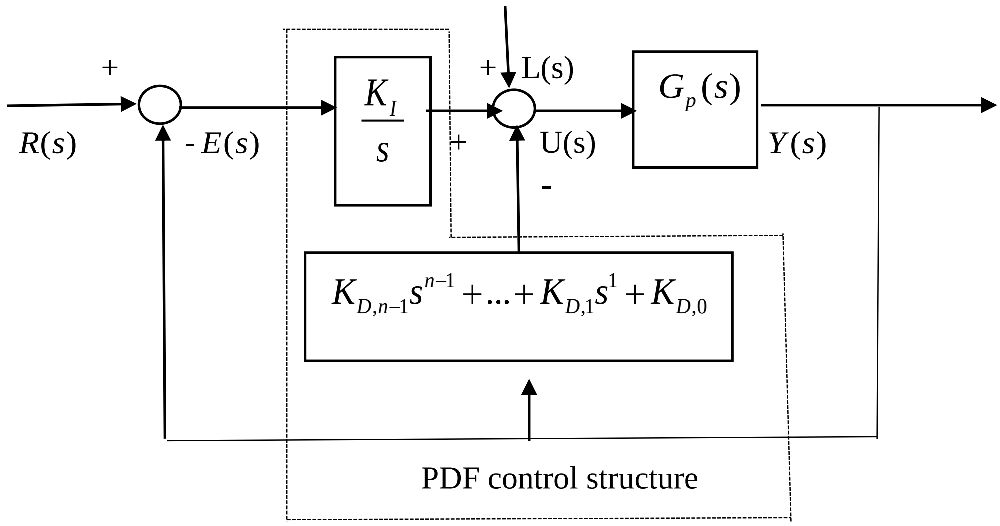

Fig.3.10. PDF control structure

In this our aims should be focussed on two forms of PDF structure, in the first only the proportional control is in the feedback and it denoted as “PD-0F” and the second forms consists of proportional and derivative control in feedback and it is denoted as “PD-1F”.

One by one each tuning method is discussed and parameters are found.

As shown in the figure the controller is "PD-0F" when $K_{D,i}$ =0, for i=1,… ,n-1 and

$K_{D,0} \equiv K_p \neq 0$ and the controller is "PD-1F" when $K_{D,0} \equiv K_p \neq 0$, $K_{D,1}$ =$K_d \neq 0$ and $K_{D,i}$ =0, for i=2… n-1.

For the above we should analyse for both the controller for the above shown IPDT model.

PD-0F Controller Settings for IPDT models [8]:

The PD-0F controller parameters can be chosen as

$$K_p = 4\pi^2 \left[\left((8-\alpha)\pi^2 + \alpha^2 \right) dK \right]^{-1}$$
$$K_I = \alpha\left(\pi^2 - \alpha\right)\left[\left((8-\alpha)\pi^2 + \alpha^2 \right) d^2 K \right]^{-1} \quad (36)$$

Where α is an adjustable parameter, in order to obtain preferred damping ratio (see [8], for details).

Alternative PD-0F Controller for IPDT models:

The PD-0F controller parameters

$$K_p = 4\left[\left(8-\beta\right) dK \right]^{-1}$$
$$K_I = \beta\left[\left(8-\beta\right) d^2 K \right]^{-1} \quad (37)$$

K_p = 161.0024, K_I = 0.077137

Where $\beta = \alpha\left(\pi^2 - \alpha\right)\pi^{-2}$

PD-1F Controller Settings for IPDT models:
The PD-1F controller parameters

$$K_p = 16\left[\left(16-3\gamma\right) dK \right]^{-1}$$
$$K_I = 4\gamma\left[\left(16-3\gamma\right) d^2 K \right]^{-1} \quad (38)$$
$$K_d = \left(8-\gamma\right)\left[\left(16-3\gamma\right) K \right]^{-1}$$

Where γ is an adjustable parameter, in order to obtain preferred damping ratio (see [8], for details).

K_p = 169.195, K_I = 0.0426, K_d = 426.834

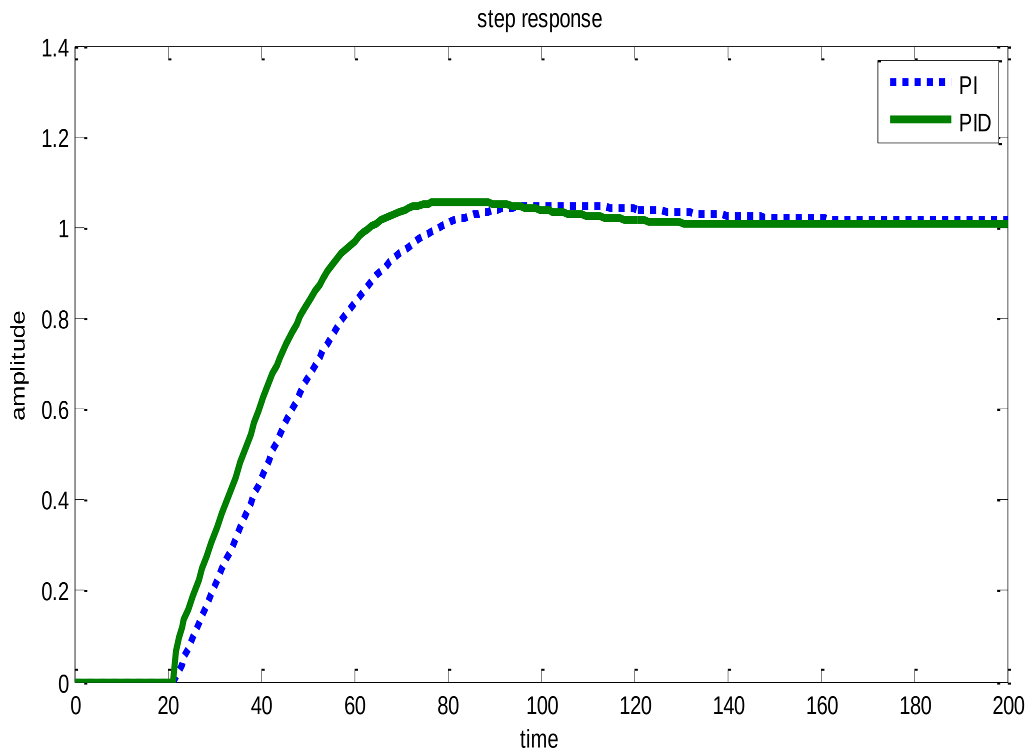

Fig.3.11. step response of PDF controller

Using Pseudo Derivative Feedback controller for IPDT plant model we got to know that PD-1F which is equivalent to PID has a good rise time compared to PI and minimum overshoot and settles faster than PI controller.

4. Simulation of FOPDT

Simulation is done using Simulink. Using above mentioned tuning formula and we have compared the P controllers of all the above tuning rules and made analysis, after that similarly for PI and PID .The solution to the proportional control case is developed first because it serves as a stepping stone for tackling the more complicated cases of stabilization using a PI or a PID controller. The proportional control stabilization problem for first-order systems with time delay can be solved using other techniques such as the Nyquist criterion and its variations. The approach presented here, however, allows a clear understanding of the relationship between the time delay exhibition by a system and its stabilization using a constant gain controller.

The objective of finding parameters through different tuning methods and analysing which method control performance in good and stable.

SIMULATION using P control [similar to Appendix (**A.3**)]:

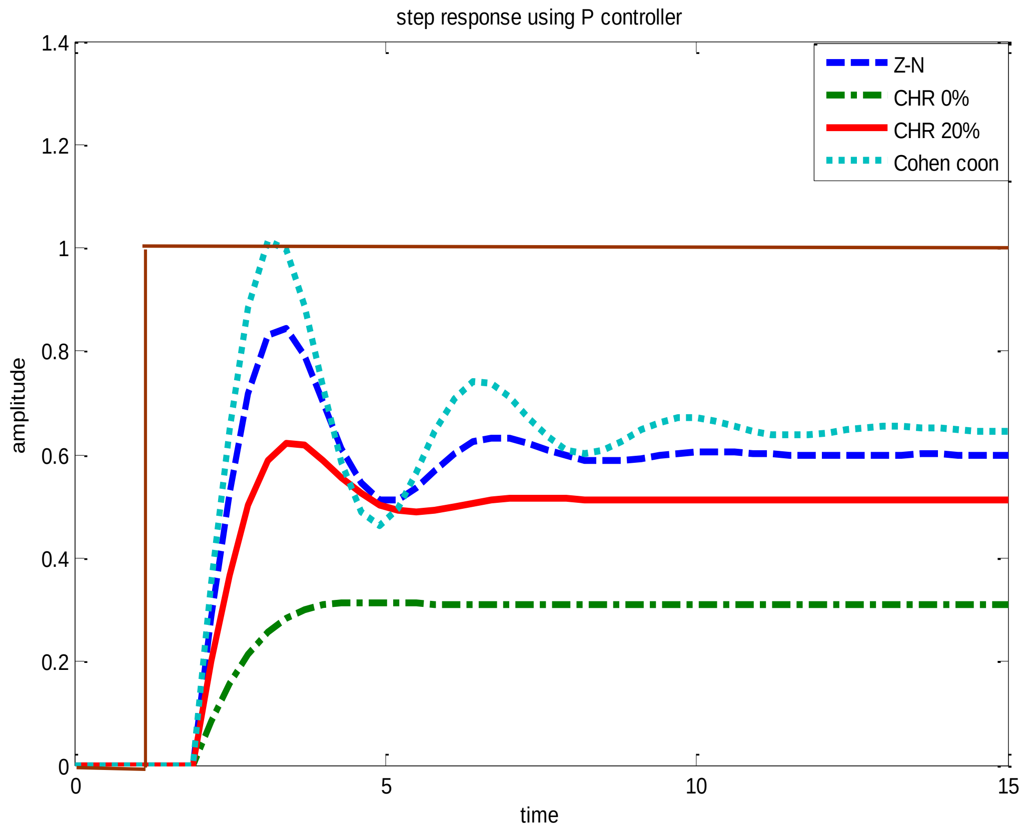

Fig.4.1.step response using P controller

As we observe from Fig.4.1 using P controller Cohen coon is faster compared to other tuning rules but it also tends to large overshoot and in Chine-Hrones-Reswick 0% overshoot, comparatively has minimum overshoot but it is slow in reponse. As it is a P controller it introduces steady state error it is difficult for all the above tuning rules the Ziegler-Nichols, the

Cohen-coon,the Chine-Hrones-Reswick 0% overshoot and 20% overshoot to get good control performance.

SIMULATION using PI controller [similar to Appendix (**A.3**)]:

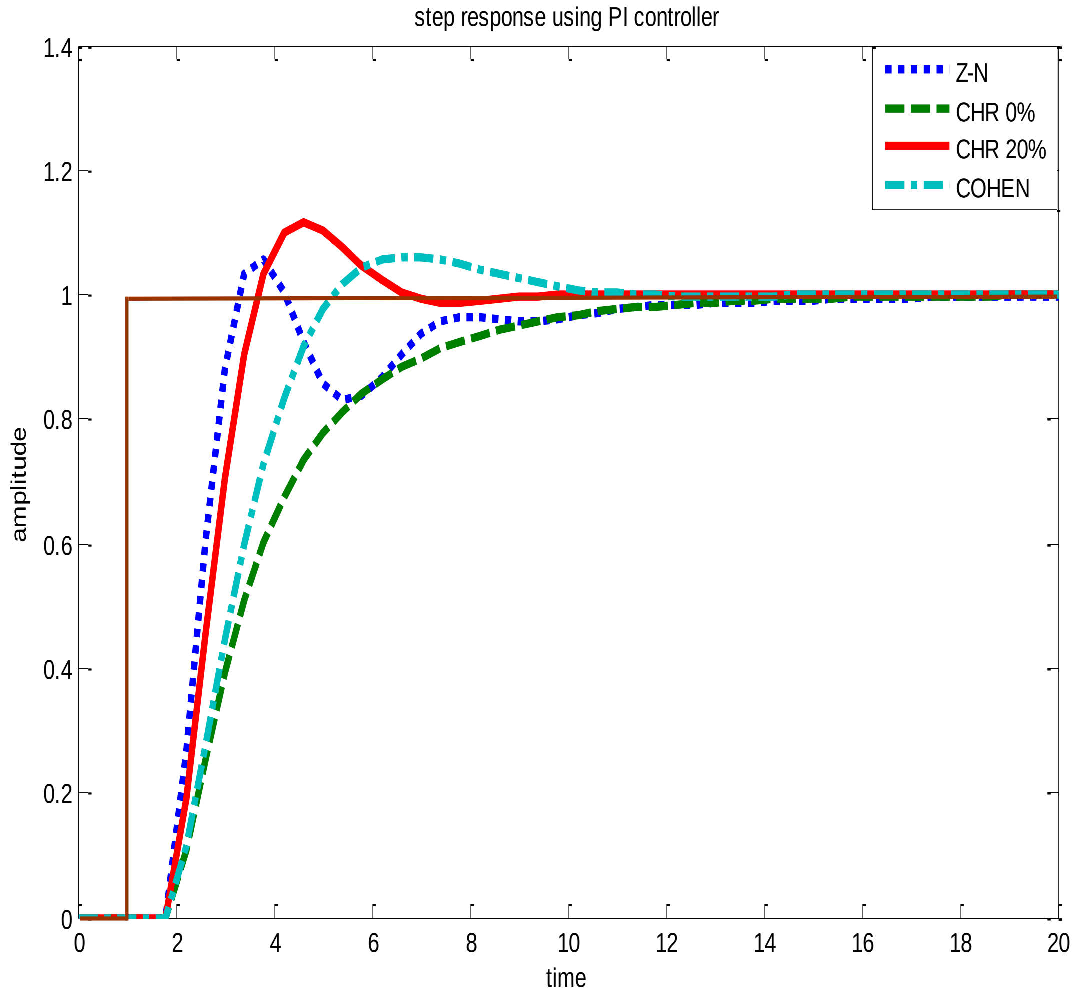

Fig.4.2.step response using PI controller

While using a PI controller to control the first-order plus dead time plant we observe that there is a quick response due to P control and the steady state error is zero due to I control, Ziegler-Nichols takes around 15 sec, Chine-Hrones-Reswick 20% overshoot and Cohen-coon has almost equal settling time of 11 sec, Chine-Hrones-Reswick 0% overshoot takes 13 sec to settle. Ziegler-Nichols responds faster than other tuning methods mentioned above.

While doing the simulation it is important to select the controllers depending upon the type of tuning of the PI controller to achieve desired controller performance while maintaining closed loop stability.

SIMULATION using PID controller [see Appendix (**A.3**)]:

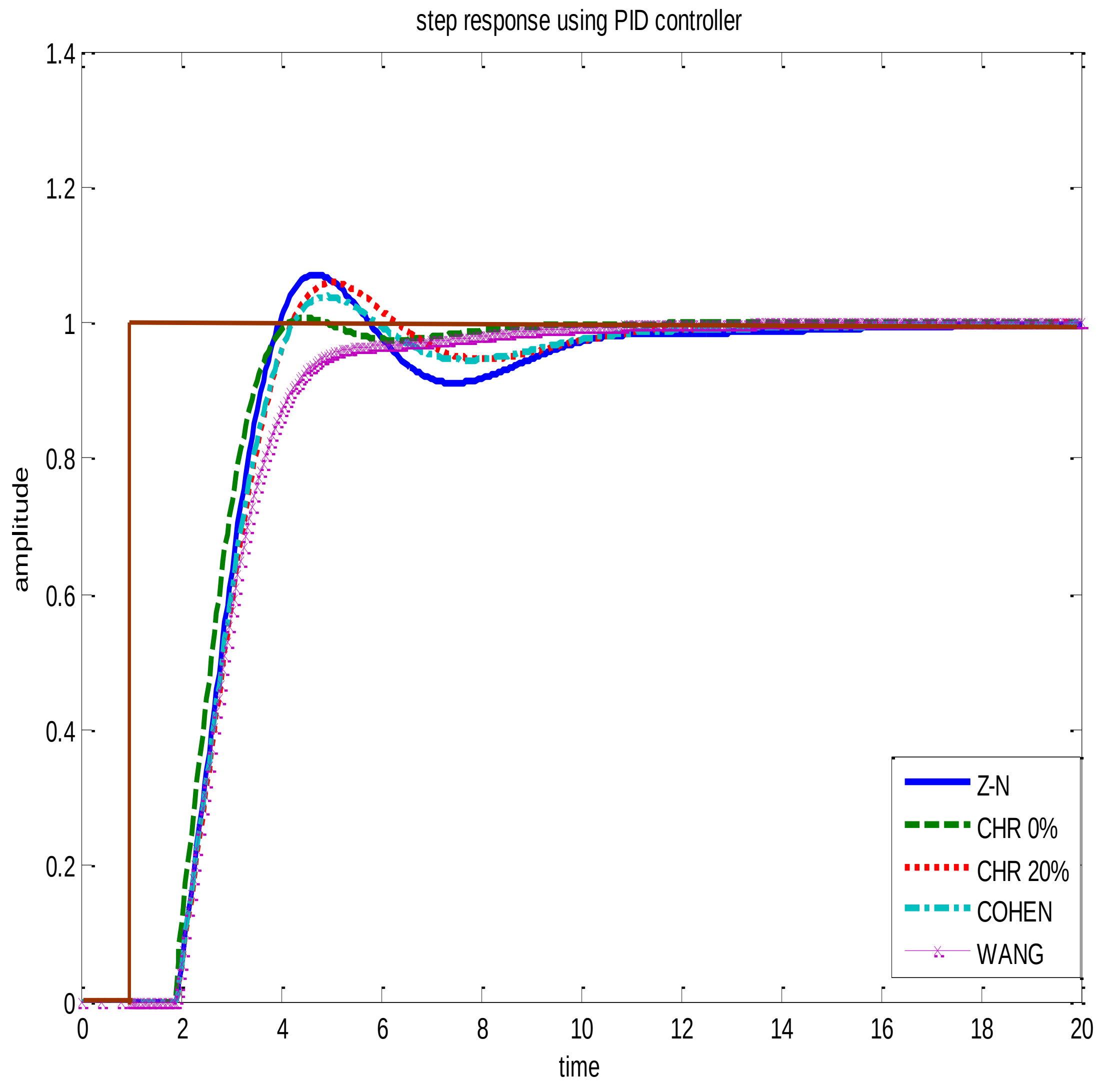

Fig.4.3.step response using PID controller

By using PID controller we are able to minimize the overshoot, quick settling time and rise time. In the above plot we analyse that Wang-Juang-Chan has a good response compared to others as there is no overshoot and also settles by 9 sec. Chine-Hrones-Reswick 0% overshoot tuning has a quick response compared to above mentioned tunings.

5.5 Optimal PID Controller Design:

Tuning methods based on the minimization of ISE guarantee small error and very fast response. However, the closed-loop step response is very oscillatory, and the tuning can lead to excessive controller output swings that cause process disturbances in other control loops.

For Set point tracking:

PI controller

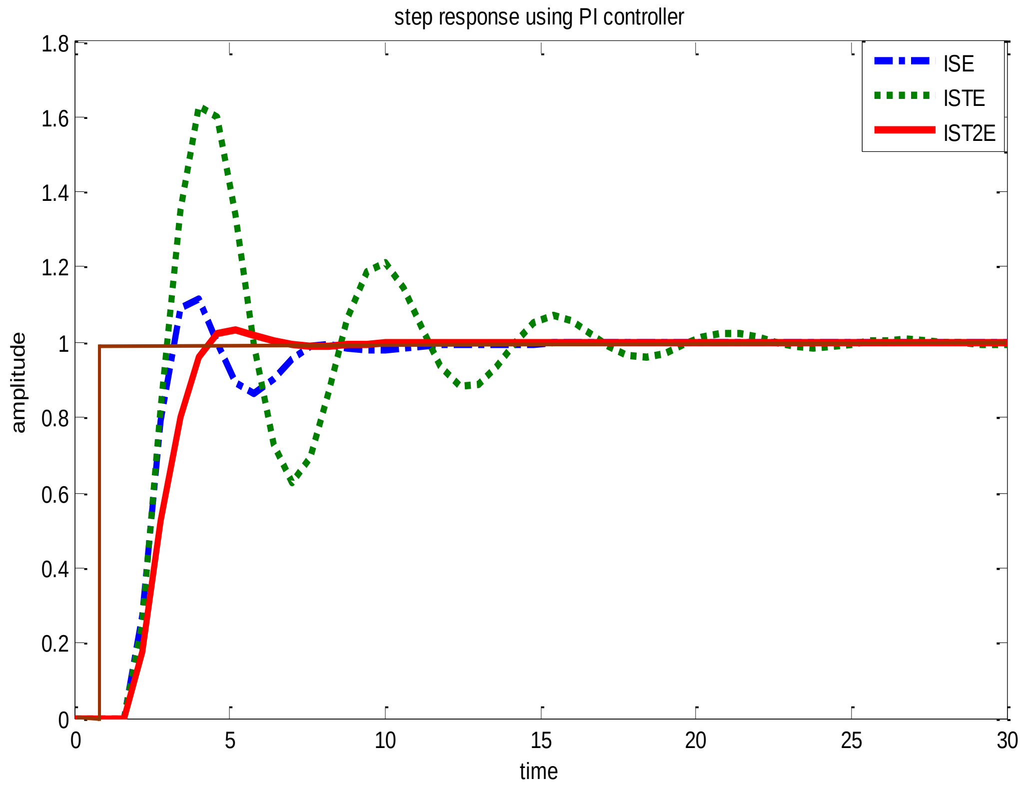

Fig.4.4.step response using PI controller

In the above plot it's been analysed that IST2E has settling time of 7 sec but it is slow in response and in ISE rise time is 1.5 sec almost equal to ISTE but lesser overshoot so its settling time is about 11 sec and on the other ISTE has a large overshoot so it take more time for the quarter amplitude decay we can do this in matlab simulation [similar to Appendix (**A.4**)]..

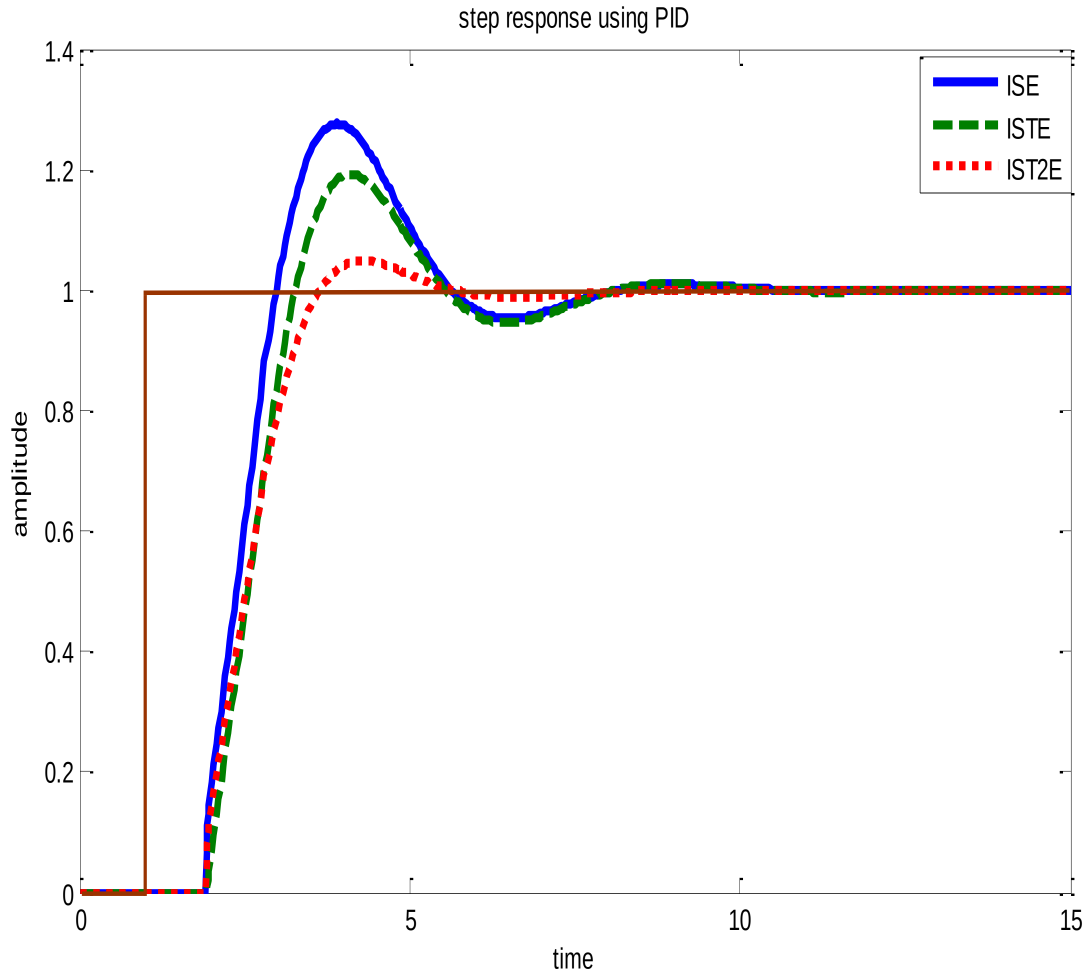

Fig.4.5.step response using PID controller

Furthermore Comparatively PID is showing better control performance than PI. Here also IST2E settles down quickly and also has a minimum overshoot compared to ISE and ISTE but its response is slow. IST2E settles in about 7 sec. and ISE settles in 12 sec. and ISTE settles in 10 sec. ISE has a faster response compared to others as one can see from the above plot by simulation [see Appendix (**A.4**)].

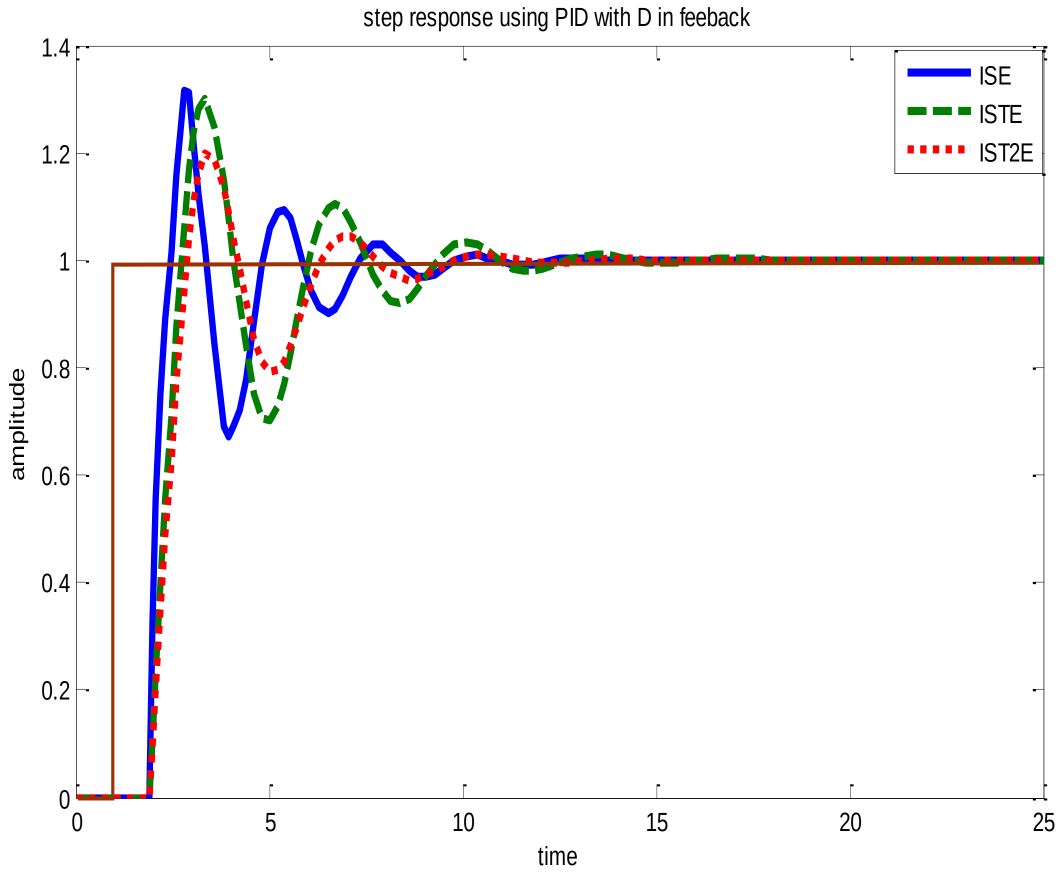

Fig.4.6.step response using PID controller

As we can say that in feedback path if we have derivative in the PID controller it may be easy & fast related to the typical Proportional-Integral-Derivative controller but we don't get a good result in its performance. Therefore if you are thinking of designing it do use a dedicated algorithm for good control performance.

Here IST2E shows a better response compared to ISE and ISTE as it has minimum overshoot so it settles quickly.

5. CONCLUSION:

Project study on PID controller design for various plant model provide a brief idea of plant modelling, type of plant model and controllers (P, PI, PD and PID) tuning method used for the of the model plant.

Discussed Plant modelling which will help in modelling of many industrial plant. And tuning method used for that plant will help to find out of controllers parameters. Response will suggest which tuning method is better for the plant. And also it will play great roll in selecting of controller.

For tuning of controllers of FOPDT Ziegler-Nichols tuning formula, Chine-Hrones-Reswick PID tuning algorithm, Cohen-Coon Tuning algorithm, Wang-Juang-Chan tuning formula and optimal PID controller design are used and what we observed is that for P controller tuning Cohen coon performs better compared to other tuning and for PI controller tuning Zeigler Nichols tuning is best suited for controlling than others and for PID controller tuning CHR 0% overshoot resulting in quick response and better settling time for the experimentally obtained IPDT model Pseudo Derivative Feedback controller is used and for this PID controller is having a good control behaviour compared to PI.

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Appendix

Matlab Source code

A.1 for finding step response of the process plant.

```
clc;

close all;

clear all;

s=tf('s');

Gp=10/(s+4)/(s+3)/(s+2)/(s+1);

step(Gp);

k=dcgain(Gp);
```

A.2 Smith Predictor deisgn.

```
s = tf('s');
P = exp(-0.855*s) * 0.4167/(1.365*s+1);
P.InputName = 'u'; P.OutputName = 'y';
P

P =

  From input "u" to output "y":
                      0.4167
  exp(-0.855*s) * -----------
                    1.365 s + 1

Continuous-time transfer function.

 step(P), grid on


Cpi = pid(1.1749,1.1815);
Cpi

Cpi =


             1
  Kp + Ki * ---
             s

  with Kp = 1.17, Ki = 1.18

Continuous-time PI controller in parallel form.
```

```
Tpi = feedback([P*Cpi,1],1,1,1);  % closed-loop model
[ysp;d]>y
Tpi.InputName = {'ysp' 'd'};

step(Tpi), grid on


Kp3 = [1.176;1.180;1.185];      % try three increasing values
of Kp
Ti3 = repmat(Cpi.Ti,3,1);   % Ti remains the same
C3 = pidstd(Kp3,Ti3);       % corresponding three PI
controllers
T3 = feedback(P*C3,1);
T3.InputName = 'ysp';

step(T3)
title('Loss of stability when increasing Kp')


F = 1/(20*s+1);
F.InputName = 'dy'; F.OutputName = 'dp';


% Process
P = exp(-0.855*s) * 0.4167/(1.365*s+1);
P.InputName = 'u'; P.OutputName = 'y0';

% Prediction model
Gp = 0.4167/(1.365*s+1);
Gp.InputName = 'u'; Gp.OutputName = 'yp';

Dp = exp(-0.855*s);
Dp.InputName = 'yp'; Dp.OutputName = 'y1';

% Overall plant
S1 = sumblk('ym = yp + dp');
S2 = sumblk('dy = y0 - y1');
Plant = connect(P,Gp,Dp,F,S1,S2,'u','ym');

% Design PI controller with 0.08 rad/s bandwidth and 90
degrees phase margin
Options = pidtuneOptions('PhaseMargin',90);
C = pid(1.1749,1.1815);
C.InputName = 'e'; C.OutputName = 'u';
C

C =
           1
Kp + Ki * ---
           s
```

```
  with Kp = 1.17, Ki = 1.18

Continuous-time PI controller in parallel form.
```

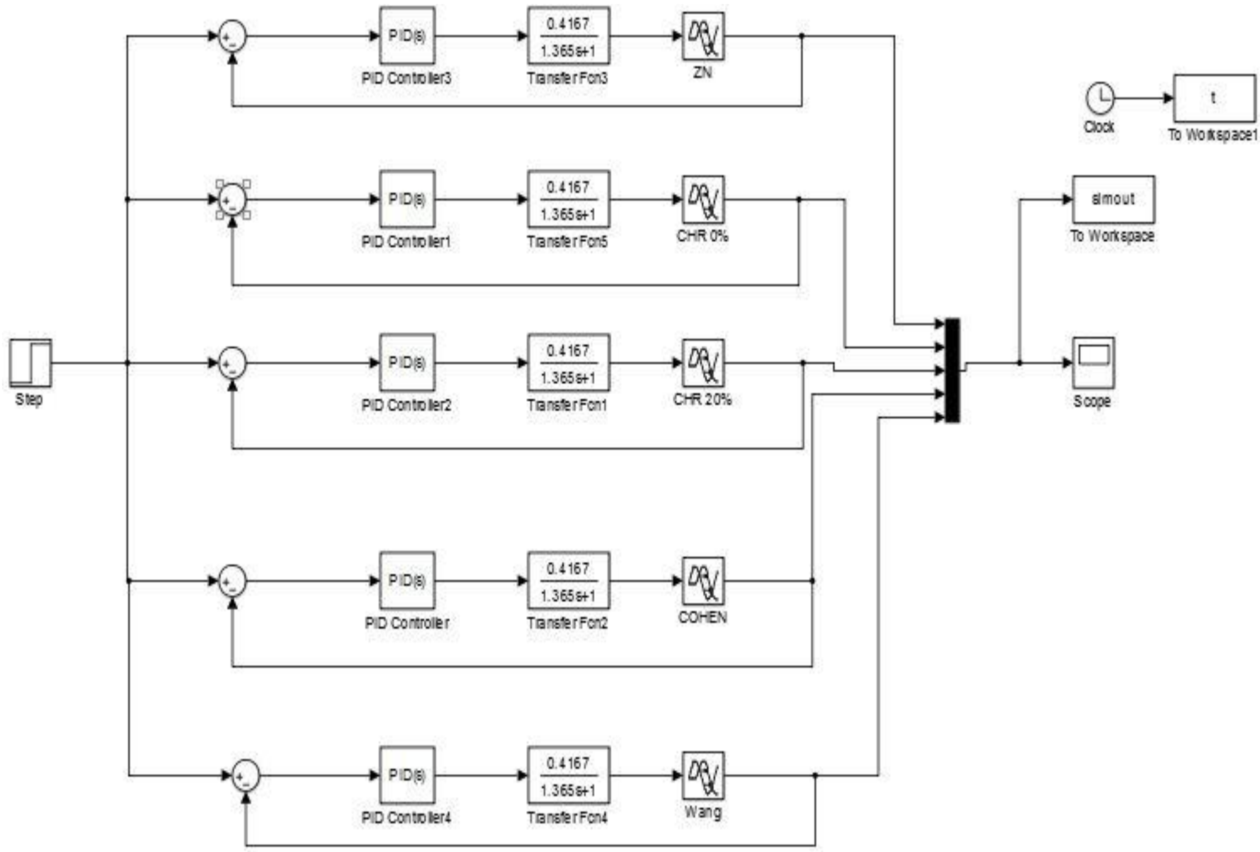
```
% Assemble closed-loop model from [y_sp,d] to y
Sum1 = sumblk('e = ysp - yp - dp');
Sum2 = sumblk('y = y0 + d');
Sum3 = sumblk('dy = y - y1');
T = connect(P,Gp,Dp,C,F,Sum1,Sum2,Sum3,{'ysp','d'},'y');
```

Use STEP to compare the Smith Predictor (blue) with the PI controller (red):

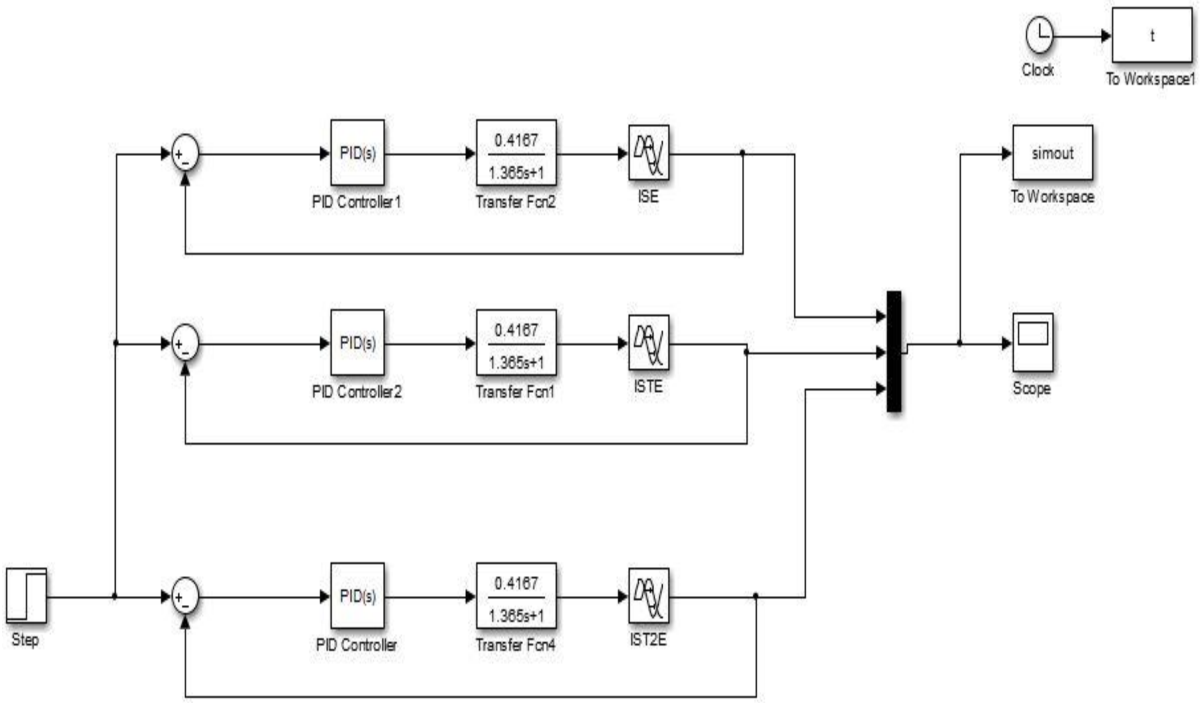
```
step(T,'b',Tpi,'r--')
grid on
legend('Smith Predictor','PI Controller')
```

```
bode(T(1,1),'b',Tpi(1,1),'r--',{1e-3,1})
grid on
legend('Smith Predictor','PI Controller')
```

A.3



A.4



Clock
t
To Workspace1
PID(s)
PID Controller1
0.4167
1.365s+1
Transfer Fcn2
ISE
simout
To Workspace
PID(s)
PID Controller2
0.4167
1.365s+1
Transfer Fcn1
ISTE
Scope
Step
PID(s)
PID Controller
0.4167
1.365s+1
Transfer Fcn4
IST2E

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