Tuning of Internal Model Control –Proportional Integral Derivative Controller for Optimized Control

Thesis submitted in partial fulfilment of the requirement for the award of Degree of

MASTER OF ENGINEERING

In
Electronic Instrumentation and Control Engineering

Submitted By

Chetan Chauhan

(801151010)

Under the Guidance of

Dr. Gagandeep Kaur

Assistant Professor

July 2013

Department of Electrical and Instrumentation Engineering,
Thapar University,
Patiala
(Established under the section 3 of UGC act, 1956)
Patiala, 147004

CERTIFICATE

I hereby certify that the work being presented in this thesis entitled **" Tuning of IMC PID Controller for Optimized Control"** in partial fulfilment of award of degree of **Master of Engineering in Electronic Instrumentation and Control,** submitted in Electrical and Instrumentation Engineering Department, Thapar University, Patiala, is an authentic record of my own work carried under the supervision of **Dr. Gagandeep Kaur,** Assistant Professor, Department of Electrical and Instrumentation Engineering, Thapar University, Patiala, Punjab.

Date: 15/07/2013

Chetan Chauhan

801151010

I certify that the above statement made by the student is correct to the best of my knowledge and belief.

Date: 15/07/2013

Dr. Gagandeep Kaur

Assistant Professor
Department of Electrical and
Instrumentation Engineering
Thapar University, Patiala,
Punjab

Countersigned By

Dr. Smarajit Ghosh

Head of Department
Department of Electrical and
Instrumentation Engineering
Thapar University, Patiala,
Punjab

Dr. S.K. Mohapatra

Dean of Academic Affairs
Thapar University, Patiala,
Punjab

ACKNOWLEDGEMENT

First of all I would like to thank our College Director, **Dr. K.K. Raina** for his valuable support. I am also thankful to our Head of the Department, **Dr. Smarajit Ghosh** as well as, the entire faculty and staff members of Electrical and Instrumentation Department who devoted their valuable time and helped me in all the possible ways towards successful completion of this work. I would like to express my deep gratitude to **Dr. Gagandeep Kaur,** Assistant Professor, Department of Electrical and Instrumentation Engineering, Thapar University, Patiala for her patient guidance and support throughout this thesis work. I am truly fortunate to have the opportunity to work with her. I am greatly indebted to all my friends, who have graciously applied themselves to the task of helping me with ample morale support and valuable suggestions. Finally, I would like to thank my parents for their years of unyielding love and encouragement. They have always wanted the best for me and I admire their determination and sacrifice.

Chetan Chauhan

(801151010)

III

ABSTARCT

Time delays are usually unavoidable in the engineering systems like mechanical and electrical systems etc. The presence of delay causes unwanted impacts on the system under consideration which imposes strict limitations on achievable or targeted feedback performance in both continuous and discrete systems. The presence of the delay complicates the design process as well. It makes continuous systems to be infinite dimensional and also it significantly increases the dimensions in discrete systems. As the internal model control based proportional integral derivative controller are simple and robust to handle the model uncertainties and disturbances. But they are less sensitive to noise than proportional integral derivative controller for an actual process in industries. It results in only one tuning parameter which is closed loop time constant λ internal model controller filter factor. It also provides a good solution to the process with significant time delays which is actually the case with working in real time environment. So in this thesis internal model control based proportional integral derivative controller is designed. The Pade's approximation for the time delay has been used because most of the controller design based on different methods can not be used with the delayed systems. While comparing the responses of the transfer functions of different kinds of orders the internal model control based proportional integral derivative controller will not give the same results as the internal model control strategy because of approximation used for delay time. Also the standard internal model filter from $f(s) = 1 / (\lambda s + 1)$ shows good set point tracking. Thus internal model control based proportional integral derivative controller is able to compensate for disturbances and model uncertainty while open loop control is not. Internal model control is also detuned to assure stability even if there is model uncertainty.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABRREVIATIONS

IMC	Internal Model Control
PID	Proportional Integral Derivative Control
PI	Proportional Integral
AMIGO	Approximate M Constrained Integral Gain Optimization
NCS	Network Controlled System
FOPD	First Order Plus Time Delay
ZN	Ziegler Nichols
GIMC	Internal Model Controller
Gf(s)	Low Pass Filter
CPID	Proportional Integral Derivative Controller
CPI	Proportional Integral Controller
λIMC	Tuning Parameter of Internal Model Controller
kcr	Critical Gain or Ultimate Gain
tcr	Critical Period or Ultimate Period
τd	Derivative time
τc	Time Constatnt
τi	Integral Time
kc	Controller Gain

CHAPTER 1

TYPES OF CONTROLLERS

2.1 Introduction

Controller design is the most essential and important part of the control applications. There are many types of controller architectures which are available in control literature, research papers and books. The controller can be either of conventional type in nature or can be of intelligent type in nature. The human intelligence does not possess by the conventional controller whereas human intelligence is embed with the help of certain soft computing algorithms in the intelligent controller. The performance evaluation part comes in to action after the design of controller is performed. The designed controller has to give optimal control results irrespective of every situation like plant and equipment non linearity, equipment saturation.

The mathematical modelling of the process requires experimental plant data and then equivalent mathematical modelling of the control scheme is made. Different kinds of controllers can be designed to meet the control scheme. The controller is actually establishing the parameters and set point as per the requirement of the process.

To meet the control scheme of the process there are following types of controller can be implemented.

i. Feedback controller
ii. Feedback plus feed forward controller

On the basis of feedback relatively the feedback controller is designed and by combining feedback and feed forward relatively feedback plus feed forward controller can be designed. But they were unable to give satisfactory results because of their inherent disadvantages and more tuning parameters. So, because of only one tuning parameter as compared to three tuning parameters of proportional integral derivative controller a model based controller is designed. The model based controller gives a satisfactory result as it has only one tuning parameter**.**

2.1.1 Feed Back Control System

Feedback control is a control mechanism which regulates the controlled variable by taking negative feedback from the output and taking regulatory action through the controller and changing the manipulating variable accordingly.

The most elementary feedback control system has three components: a plant (the object to be controlled, no matter what it is, it is always called as the plant), a sensor to measure the output of the plant, and a controller to generate the plant's input. The actuators are lumped in with the plant. The block diagram of elementary control system is shown in Figure 2.1. All the blocks of block diagram have two inputs i.e. One input is internal to the system and the other input is coming from outside. Every block has one output also.

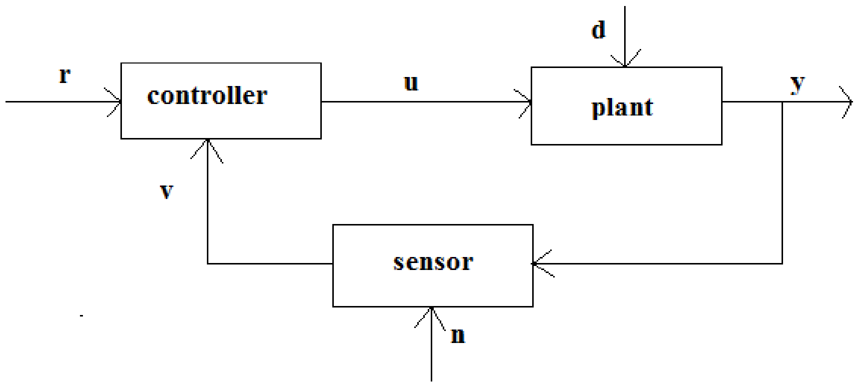

Figure 2.1: Block diagram of Elementary control system.

These signals have the following interpretations

r is the reference or command input
v is the sensor output
u is the actuating signal or plant input
d is the external disturbance
y is the plant output and measured signal
n is the sensor noise

The three signals r, d, and n which are coming from outside are called exogenous inputs. Some pre specified function of r can be approximate by y and it should do so in the presence of the disturbance d, sensor noise n with uncertainty in the plant and knowledge of y is obtained from v. The analysis is done in the frequency domain.

Each of the three components in Figure 2.1 is assumed to be linear. So its output is a linear function of its input. The plant equation has

$$y = P\,(d / u) \tag{2.1}$$

y is the plant output and measured signal

P is the plant

D is the external disturbance

U is the actuating signal or plant input

Partitioning the 1 × 2 transfer matrix P as

$$P = [P1, P2] \tag{2.2}$$

$$y = P\,1\,d + P\,2\,u \tag{2.3}$$

The outputs of the three components are linear functions of the sums or difference of their inputs that is the plant, sensor, and controller. The block diagram of these equations is shown in Figure 2.2.

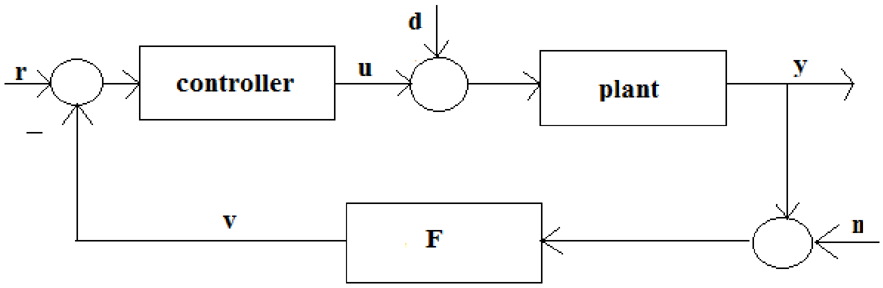

Figure 2.2: Block diagram of Basic Feedback loop.

The equations of these are taken in the form of

$$y = P\,(d + u) \tag{2.4}$$

$$v = F\,(y + n) \tag{2.5}$$

$$u = C\,(r - v) \tag{2.6}$$

P is the Plant

F is the sensor or feed back

C is the controller

The transfer functions of all physical systems have to be strictly proper because the amplitude of the output will go to zero if a sinusoid of ever-increasing frequency is applied to a linear, time-invariant system. This will lead to misleading results. A real system will cease to behave linearly as the frequency of the input increases. The transfer functions will be used to parameterize an uncertainty set and it may be convenient to allow some of them to be only proper. A proportional integral derivative controller is very common in practice especially in chemical engineering. It has the form

$$k1 + k2 / s + k3s \quad (2.7)$$

k1, k2, k3 are the gains of PID controllers

This is not proper, but it can be approximated over any desired frequency range by a proper one which is showing below.

$$(k1) + (k2 / s) + (k3s / \tau s + 1) \quad (2.8)$$

The feedback system is automatically well-posed, in the stronger sense, if P, C, and F are proper and one is strictly proper. P is strictly proper, C and F are proper [5].

2.1.2 Feedback plus feed forward controller

It is one of the most widely used advanced control techniques in the process control industry. Feed forward offers many advantages over feedback control. Feed forward can compensate for load upsets before they are detected by the feedback control system as an error. Feedback controllers can only react to correct for a load upset after an error is detected between the process variable and the setpoint. Properly tuned feedback/feed forward controllers can reduce load disturbances to controlled process variable measurement by a factor of 10 better than feedback control alone. The Block Diagram of Feedback Plus Feed forward Control System of a Self-Regulating Process is shown in figure 2.3.

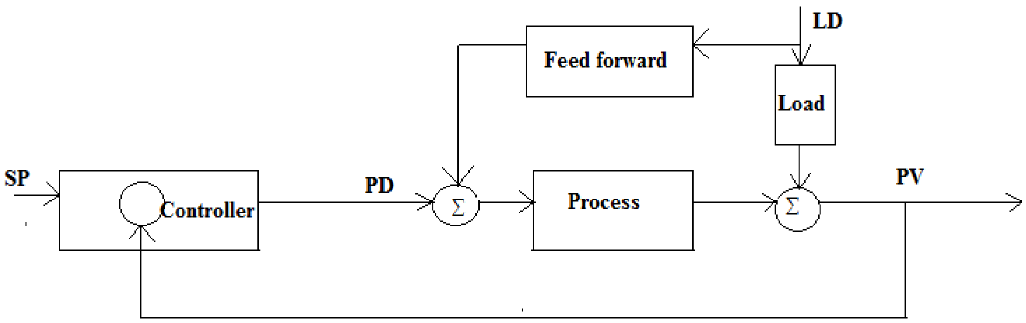

Figure 2.3: Block Diagram of Feedback Plus Feed forward Control System of a Self-Regulating Process

In a feedback control system a load upset disturbs the process variable measurement. The system stays upset until the feedback control brings the process variable measurement back to setpoint. Feed forward control can be used to improve the response of the system under these circumstances. The basic principle of feed forward control is to measure the disturbances as they occur, and to make adjustments to the process demand signal of the feedback controller preventing the disturbance from upsetting the process variable signal being controlled.

As shown in figure 2.3 the control system has two process demand signals i.e., two variables that when changed effect the controlled variable. The two process demand signals are

PD1 is the controller output

PD2 is the measured load upset

The control system has only one controlled process variable PV2

In normal feedback control the controller determines the error SP1 - PV1 and adjusts the controller output PD1 to bring the error to zero as a function of the PID parameters in the controller. With feed forward added to the control loop the output of the controller PD1 is also changed as a function of a measured load disturbance PD2. The tuning parameters for the feed forward for self-regulating processes are typically in the terms of gain, lead/lag, and delay. The feed forward gain tells about the speed of lead/lag and the delay is when to change the valve position to correct for a changing load disturbance so the measured process variable will not be disturbed [5].

2.2 Types of Controllers

The different types of controllers designed to meet control scheme of the plant are as follows

i. Automatic controller
ii. Industrial controller

2.2.1 Automatic Controller

To compare the actual value of plant result with reference command, determines the difference, and produces a control signal that will reduce this difference to a negligible value an automatic controller is used . The manner in which the automatic controller produces such a control signal is called the control action.

2.2.2 Industrial controller

An industrial control system consists of an actuator, an automatic controller, a plant, and a sensor measuring element. The actuating error command at a very low power level is detected by the controller and amplifies it to a very high level. The automatic controller output is fed to actuators which are an electric motor or hydraulic motor, or a pneumatic motor or valve or any other sources of energy. The input to the plant according to the control signal is produced by actuator so that the output signal will point to the reference input signal. The device that converts the output variable into another optimum variable, such as a displacement, pressure or voltage that can be used to compare the output to the reference input command is sensor or the measuring element. This element is in a feedback path of the closed loop system. The set point controller must be converted to reference input with the same unit as the feedback signal from the sensor element.

2.2.2.1 Classification of Industrial Controller

Industrial controllers may be classified according to their control action as

a) Two-position or on-off controllers
b) Proportional controllers
c) Proportional-plus-derivative controllers
d) Proportional-plus-integral controllers
e) Proportional-plus-integral-plus-derivative controllers
f) Phase –lag controller
g) Phase-lead-lag controller
h) Rate feedback controller
i) IMC controller

Depending upon the nature of the plant and the operating condition, such as safety, cost, availability, reliability, accuracy, weight and size, the usage of different types of controllers is decided.

a. Two position or on - off controllers

In a two-position control system, the actuating part has only two fixed positions, which are, in many simple cases, simply on and off. It is being very widely used in both industrial and domestic control system due to its simplicity and inexpensiveness. The output signal from the controller be u(t) and the actuating error signal be e(t). The mathematically form is showing below.

$$u(t) = U1, \text{ for } e(t) > 0 \quad (2.9)$$

$$u(t) = U2, \text{ for } e(t) < 0 \quad (2.10)$$

u(t) is the output signal

U1 and U2 are constants. The minimum value of U2 is usually either zero or -U1

b. Proportional controllers

A Proportional control system is a type of linear feedback control system. The proportional control system is more complex than an on-off control system like a bi-metallic domestic thermostat but simpler than a proportional-integral-derivative (PID) control system. It used in an automobile cruise control. Where the overall system has a relatively long response time On-off control will work but will result in instability if the system being controlled has a rapid response time. Proportional control overcomes this by modulating the output to the controlling device, such as a continuously variable valve [23]. The proportional controller block diagram is shown in figure 2.4.

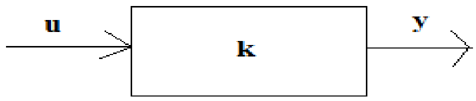

Figure 2.4: Proportional controller block diagram

An analogy to on-off control is driving a car by applying either full power or no power and varying the duty cycle, to control speed. The power would be on until the target speed is reached, and then the power would be removed so the car reduces speed. When the speed falls below the target, with a certain hysteresis full power would again be applied. It can be seen that this looks like pulse-width modulation but would obviously result in poor control and large variations in speed. The more powerful the engine, the greater the instability, the heavier the car the greater the stability. Stability may be expressed as correlating to the power-to-weight ratio of the vehicle.

Proportional control is like to control the speed of a car. If the car is at target speed and the speed increases slightly, the power is reduced slightly, or in proportion to the error. So that the car reduces speed gradually and reaches the target point with very little, if any overshoot so the result is much smoother control than on-off control. The refinements like proportional integral derivative control will help compensate for additional variables like hills where the amount of power needed for a given speed change would vary. It will be accounted for by the integral function of the proportional integral derivative control.

Proportional control theory

In the proportional control algorithm, the controller output is proportional to the error signal, which is the difference between the setpoint and the process variable. The output of a proportional controller is the multiplication product of the error signal and the proportional gain. Proportional controllers are simply gain values. These are essentially multiplicative coefficients K. The P controller can only force the system poles to a spot on the system's root locus. The P controller cannot be used for arbitrary pole placement.

This can be mathematically expressed as

$$P_{out} = K_p\, e(t) \tag{2.11}$$

P_{out} is Output of the proportional controller

K_p is the Proportional gain

$e(t)$ is the instantaneous process error at time *t*.

$$e(t) = SP - PV \tag{2.12}$$

SP is the Set point

PV is the Process variable

When the value of Kp is increased then, response speed of the system increases, overshoot of the closed-loop system increases, steady-state error decreases. But with the high value of Kp, closed-loop system becomes unstable [23].

c. Proportional-plus-derivative controllers

The derivative of a signal in the Laplace domain is as follows

$$D(s) = L\,\{f'(t)\} = s\,F(s) - f(0) \tag{2.13}$$

The equation with systems having zero initial condition is below

$$D(s) = L\{f'(t)\} = s\,F(s) \tag{2.14}$$

The derivative controllers are implemented to account for future values, by taking the derivative, and controlling based on where the signal is going to be in the future. Small amount of high-frequency noise can cause very large derivatives which appear like amplified noise. So derivative controllers should be used with carefully. Frequently solutions involving only integral controllers or proportional controllers are preferred over using derivative controllers because derivative controllers are difficult to implement perfectly in hardware or software.

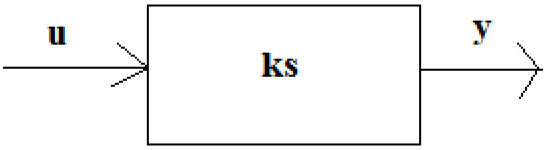

Figure 2.5: Proportional derivative controller block diagram

The derivative controllers are not proper systems because the order of the numerator of the system is greater than the order of the denominator of the system. So due to being non-proper system it is difficult to make certain mathematical analysis of these systems.

The transfer functions must be proper in order to use derivative control. So a pole is added to the controller.

$$Gpd(s) = Kp + Kds \tag{2.15}$$

$$Gpd(s) = Kp(1+Tds) \tag{2.16}$$

When the value of Td increases then the overshoot tends to be smaller, Rise time gets slower but settling time remains similar [23].

d. Proportional-plus-integral controllers

The transfer function does not possess an integrator 1/s. There is a steady-state error or offset in the response to a step input in a proportional control of a plant. If an integral controller is included in the system such an offset can be eliminated.

The control signal the output signal from the controller at any instant is the area under the actuating error signal curve up to that instant in the integral control of a plant. But it may lead to oscillatory response of slowly decreasing amplitude or even increasing amplitude while removing the steady-state error. So both of which is not desirable [23]. The proportional-integral controller block diagram is shown in figure 2.6.

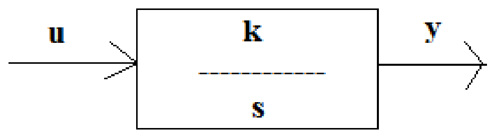

Figure 2.6: Mathematical block diagram of Proportional integral controller

The P-Only controller, the proportional-integral (PI) algorithm computes and transmits a controller output (CO) signal every sample time T to the final control element valve, variable speed pump. The computed CO from the proportional integral algorithm is influenced by the controller tuning parameters and the controller error e(t). proportional integral controllers have two tuning parameters to adjust. So it makes them more challenging to tune than a P-Only controller. They are not as complex as the three parameter proportional integral derivative controller. Integral action enables proportional integral controllers to eliminate offset, a major weakness of a P-only controller. Proportional integral controllers provide a balance of complexity and capability that makes them by far the most widely used algorithm in process control applications [23].

A proportional integral Controller proportional-integral controller is a feedback controller which drives the plant to be controlled by a weighted sum of the error difference between the output and desired set-point and the integral of that value. It is a special case of the proportional integral derivative controller in which the derivative

(D) part of the error is not used. The proportional integral controller block diagram is shown in figure 2.7.

The PI controller is mathematically given as

$$Gc = Kp + Ki / s \quad (2.17)$$

$$Gc = Kp (1 + 1 / s Ti) \quad (2.18)$$

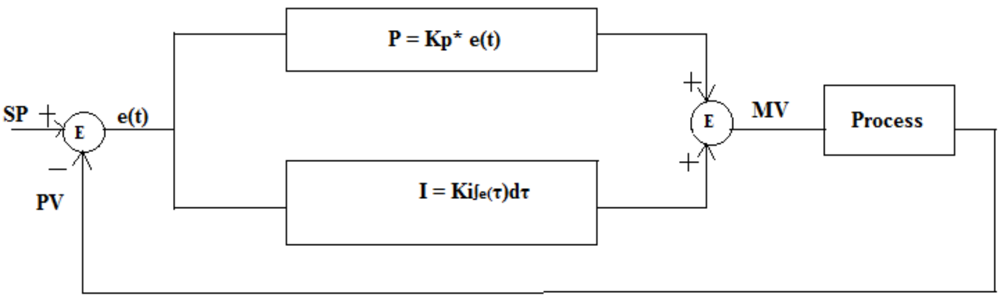

Figure 2.7: Proportional integral controller block diagram [23]

Integral control action added to the proportional controller converts the original system into high order. The control system may become unstable for a large value of Kp since roots of the characteristic equation may have positive real part. In this control, proportional control action tends to stabilize the system, while the integral control action tends to eliminate or reduce steady-state error in response to various inputs [23]. As the value of Ti is increased then overshoot tends to be smaller, speed of the response tends to be slower.

e. Proportional-plus-integral-plus-derivative controllers

The proportional integral derivative controller is a combination of proportional derivative and proportional integral controllers. PID means P for the proportional term, I for the integral term and D for the derivative term in the controller. The Three-term or proportional integral derivative controllers are probably the most widely used industrial controller. Even complex industrial control systems may comprise a control network whose main control building block is a proportional integral derivative control module. The three-term proportional integral derivative controller has had a long history of use and has survived the changes of technology from the analog era into the digital computer control system age quite satisfactorily. It was the first only controller to be mass produced for the high-volume market that existed in the process industries [23]. Block diagram of a proportional integral derivative controller in a feedback loop is shown in figure 2.8.

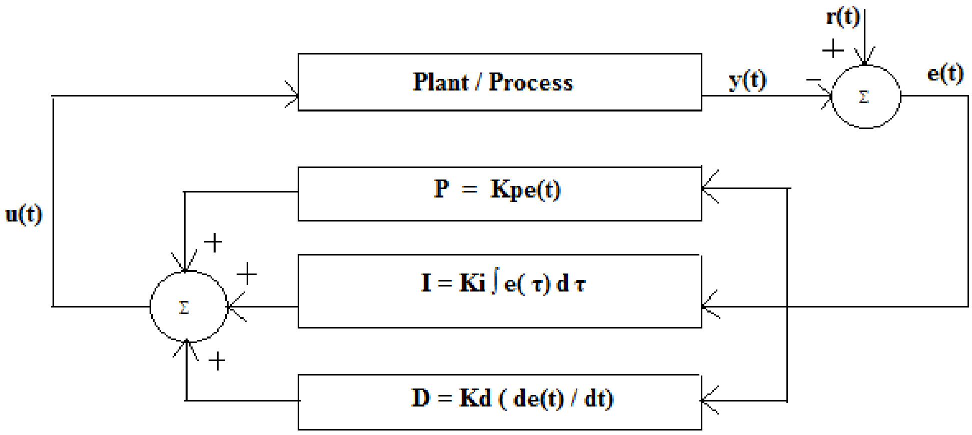

Figure 2.8: Block diagram of a proportional integral derivative controller in a feedback loop

The proportional, integral, and derivative terms are summed to calculate the output of the proportional integral derivative controller. The final form of the proportional integral derivative equation is given by

$$u(t) = MV(t) = Kpe(t) + Ki \int_0^t e(\tau)\, d\tau + Kd\, (d/dt)\, e(t) \qquad (2.19)$$

u(t) is the controller output

Kp is the Proportional gain a tuning parameter

Ki is the Integral gain a tuning parameter

Kd is the Derivative gain a tuning parameter

e is the error = SP – PV (2.20)

t is the time or instantaneous time

τ is the Variable of integration takes on values from time 0 to the present t.

Proportional term

The proportional term produces an output value that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by a constant K_p, called the proportional gain constant.

The proportional term is given by

$$Pout = Kp\ e(t) \tag{2.21}$$

A large change in the output for a given change in the error occurs due to a high proportional. If the proportional gain is too high the system can become unstable. A small gain results in a small output response to a large input error and a less responsive or less sensitive controller. If the proportional gain is too low the control action may be too small when responding to system disturbances. Tuning theory and industrial practice indicate that the proportional term should contribute the bulk of the output change.

Droop

A proportional controller generally operates with a steady-state error referred to as droop because a non-zero error is required to drive it. Droop is proportional to the process gain and inversely proportional to proportional gain. Droop may be mitigated by adding a compensating bias term to the setpoint or output or corrected dynamically by adding an integral term.

Integral term

The contribution from the integral term is proportional to both the magnitude of the error and the duration of the error. The integral in a proportional integral derivative controller is the sum of the instantaneous error over time and gives the accumulated offset that should have been corrected previously. The accumulated error is then multiplied by the integral gain Ki and added to the controller output.

The integral term is given by

$$Iout = Ki \int_{0}^{t} e(t)\, dt \qquad (2.22)$$

The integral term accelerates the movement of the process towards setpoint and eliminates the residual steady-state error that occurs with a pure proportional controller. The integral term responds to accumulated errors from the past it can cause the present value to overshoot the setpoint value.

Derivative term

The derivative of the process error is calculated by determining the slope of the error over time and multiplying this rate of change by the derivative gain K_d. The magnitude of the contribution of the derivative term to the overall control action is termed the derivative gain K_d.

The derivative term is given by

$$Dout = Kd\ (d / dt)\ e\ (t) \qquad (2.23)$$

Derivative action predicts system behaviour and thus improves settling time and stability of the system [11]. Derivative action is seldom used in practice because of its inherent sensitivity to measurement noise. The derivative action will be erratic and actually degrade control performance if this noise is severe enough. Large, sudden changes in the measured error which typically occur when the set point is changed cause a sudden large control action stemming from the derivative term. It goes under the name of derivative kick. It can be make better if the measured error is passed through a linear low-pass filter or a nonlinear but simple median filter [24].

f. Phase –lag controller

The phase-lag controller belongs to the same class as the proportional integral controller. The phase-lag controller can be regarded as a generalization of the proportional integral controller. It introduces a negative phase into the feedback loop which justifies its name. It has a zero and pole with the pole being closer to the imaginary axis i.e.

$$Gc(s) = (p1 / z1) ((s + z1) / (s + p1), \quad z1 > p1 > 0 \tag{2.24}$$

$$\arg Gc(s) = \arg (s + z1) – \arg (s + p1) = \theta z1 - \theta p1 < 0 \tag{2.25}$$

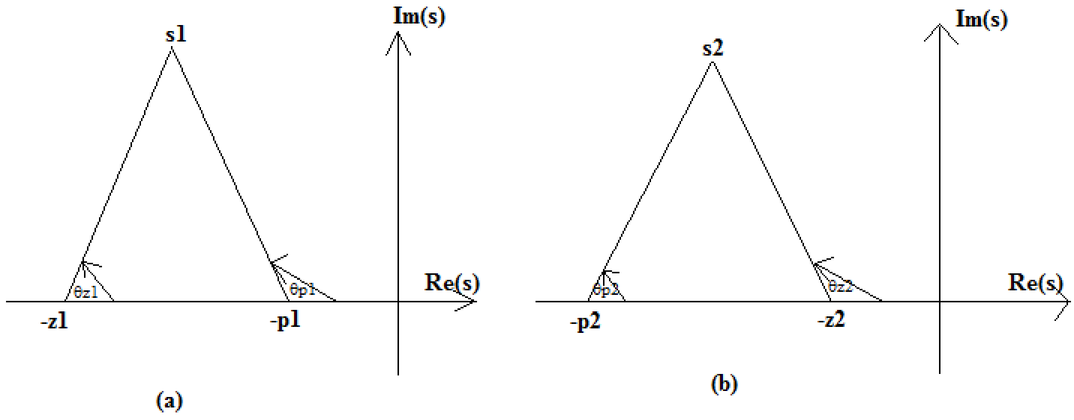

Figure 2.9: Poles and zeros of phase-lag (a) and phase-lead (b) controllers

p1/ z1 is known as the lag ratio. The corresponding angles are given in Figure 2.9 (a) and (b) The phase-lag controller is used to improve steady state errors.

g. Phase-lead-lag controller

The phase-lag-lead controller is obtained as a combination of phase-lead and phase-lag controllers. Its transfer function is given by

$$Gc(s) = (s + z1) (s +z2) / (s + p1) (s + p2), \; p2> z2> z1 > p1 > 0, \; z1 z2 = p1p2 \tag{2.26}$$

It has features of both phase-lag and phase-lead controllers, i.e. it can be used to improve simultaneously both the system transient response and steady state errors. It is harder to design phase-lag-lead controllers than either phase-lag or phase-lead controllers.

h. Rate feedback controller

The controllers explained above have simple forms and in most cases they are placed in the forward loop in the front of the system to be controlled. The rate feedback controller is always used in the feedback loop. The rate feedback controller is obtained by feeding back the derivative of the output of a second-order system or a system which can be approximated by a second-order system i.e. a system with dominant complex conjugate poles according to the block diagram given in Figure 2.10. The rate feedback control helps to increase the system damping. The closed-loop transfer function for this configuration is given by

$$Y(s) = \frac{\omega^2 n}{s^2 + 2(\zeta + (1/2)\,Kt\,\omega n)\,\omega ns + \omega^2 n} = \frac{\omega^2 n}{s^2 + 2\,\zeta c\,\omega ns + \omega^2 n}, \quad Kt>0 \quad (2.27)$$

Compared with the closed-loop transfer function of the second-order system without control we see that the damping factor is now increased to

$$\zeta c = \zeta + 1/2\,Kt\,\omega n \quad (2.28)$$

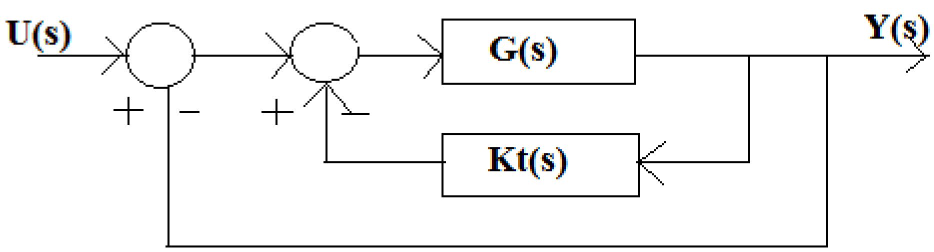

Figure 2.10: Block diagram for a rate feedback controller

Since the natural frequency is unchanged, this controller decreases the response settling time. The system response maximum percent overshoot is also decreased [14, 16].

i. Internal Model Control controller

The model based control systems are often used to track set points and reject low disturbances. The internal model control internal model control is based on the principle of the internal model. It states that if any control system contains within it implicitly or explicitly some representation of the process to be controlled then a perfect control is easily achieved. If the control scheme has been developed based on the exact model of the process then it is possible to get perfect control theoretically. The open loop control strategy is shown in figure 2.11.

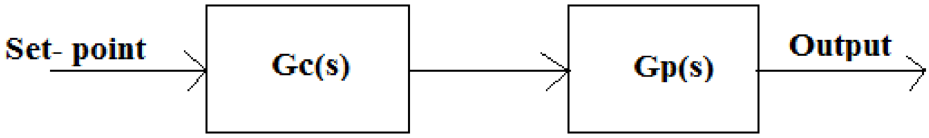

Figure 2.11: Open loop control strategy

For above open loop control system

Output is Gc. Gp. Set-point multiplication of all three parameters

Gc is the controller of process

Gp is the actual process or plant

Gp* is the model of the actual process or plant

A controller Gc is used to control the process Gp. Suppose Gp* is the model of Gp then by setting.

Gc =inverse of Gp* inverse of model of the actual process

And if

Gp is Gp***** the model is the exact representation of the actual process

The perfect control on the process can be achieved by having the complete knowledge of the process. The ideal control performance is achieved without feedback which signifies that feedback control is necessary only when knowledge about the process is inaccurate or incomplete.

The internal model control design procedure is identical to the open loop control design procedure. The implementation of internal model control results in a feedback system. So the internal model control is able to compensate for disturbances and model uncertainty while open loop control is not. The internal model control must be detuned to assure stability if there is model uncertainty [19].

The Internal Model Strategy

The process-model mismatch is common. The process model may not be invertible and the system is often affected by unknown disturbances. So the above open loop control arrangement will not be able to maintain output at setpoint. It forms the basis for the development of a control strategy that has the potential to achieve perfect control. This strategy is known as internal model control IMC. The general structure shown in Fig. 2.12

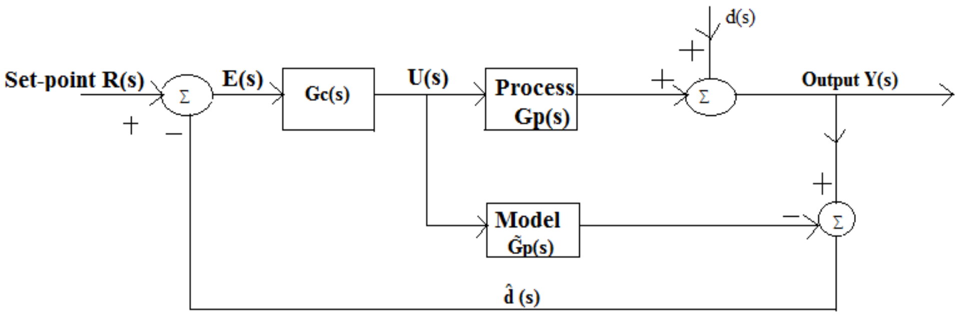

Figure 2.12: Schematic of the internal model control scheme [19]

d(s) is an unknown disturbance which affects the system as shown in the figure 2.9.

U(s) is the manipulated input which is introduced to both the process and its model

Y(s) is the process output compared with the output of the model, resulting in a signal $\tilde{d}(s)$.

$$\hat{d}\ (s) = [G\ (s) - \tilde{G}p(s)]\ U(s) + d(s) \quad (2.29)$$

$$d(s) = \text{zero} \quad (2.30)$$

Then the $\hat{d}(s)$ is the difference in behaviour between the process and its model.

$$\text{When } G\ (s) = \tilde{G}p(s) \quad (2.31)$$

$\tilde{D}(s)$ is equal to the unknown disturbance.

The $\hat{d}(s)$ is missing in the model $\tilde{G}p(s)$ so can be used to improve control. This is done by subtracting $\hat{d}(s)$ from the setpoint R(s) which is very similar to affecting a setpoint trim. The resulting control signal is given by

$$U(s) = [R(s) - \hat{d}(s)]\, Gc(s) = \{R(s) - [G(s) - \tilde{G}p(s)]\, U(s) - d(s)\}\, Gc(s) \quad (2.32)$$

$$U(s) = [R(s) - d(s)]\, Gc(s) / 1 + [G(s) - \tilde{G}p(s)]\, Gc(s) \quad (2.33)$$

$$\text{Since } Y(s) = Gp(s)\, U(s) + d(S) \quad (2.34)$$

The closed loop transfer function for the internal model control scheme is given by

$$Y(s) = \frac{[R(s) - d(s)]\, Gc(s)}{1 + [G(s) - \tilde{G}p(s)]\, Gc(s)} + d(s) \quad (2.35)$$

$$Y(s) = \frac{Gp(s)\, R(s)\, Gc(s) + 1 - [Gc(s)\, \tilde{G}p(s)]\ d(s)}{1 + [G(s) - \tilde{G}p(s)]\, Gc(s)} \quad (2.36)$$

Perfect setpoint tracking and disturbance rejection is achieved if $Gc(s) = \tilde{G}p(s)-1$ and if $G(s) = \tilde{G}p(s)$. If $G(s) \neq \tilde{G}p(s)$ perfect disturbance rejection can be realised provided $Gc(s) = \tilde{G}p(s)-1$.

The effects of process model mismatch should be minimised to improve robustness. A low-pass filter *G*f (s) is added to attenuate the effects of process-model mismatch. Since discrepancies between process and model behaviour u occur at the high frequency end of the system's frequency response. The internal model controller is designed as the inverse of the process model in series with a low-pass filter, i.e. $G_{IMC} = Gc(s)\, Gf(s)$. The order of the filter is so chosen that Gc(s) Gf(s) is proper to prevent excessive differential control action. The resulting closed loop is then given by

$$Y(s) = \frac{Gp(s)\, R(s)\, G_{IMC}(s) + 1 - [G_{IMC}(s)\, \tilde{G}p(s)]\, d(s)}{1 + [G(s) - \tilde{G}p(s)]\, G_{IMC}(s)} \quad (2.37)$$

Practical Design of Internal Model Control

It is relatively easy to design an internal model controller. $\tilde{G}p(s)$ is model of the process. First factor $\tilde{G}p(s)$ into "invertible" and "non-invertible" components.

$$\tilde{G}p(s) = \tilde{G}{+}p(s)\ \tilde{G}{-}p(s)$$

The non-invertible component, $\tilde{G}{-}p(s)$ contains terms which if inverted, will lead to instability and reliability problems terms containing positive zeros and time-delays. Set $Gc(s) = \tilde{G}{+}p(s){-}1$ and then $G_{IMC} = Gc(s)\ Gf(s)$, where $Gf(s)$ is a low-pass function of appropriate order [19].

CHAPTER 2
LITERATURE SURVEY

Costas Kravaris et al. has described that many industrially important processes feature both nonlinear system dynamics and a process dead time. Powerful dead time compensation methods, such as the Smith predictor, are available for linear systems represented by transfer functions. A Smith predictor structure in state space for linear systems is presented first and then directly extended to nonlinear systems. When combined with input /output linearizing state feedback, this Smith-like predictor makes a nonlinear system with dead time behave like a linear system with dead time. The control structure is completed by adding an external linear controller, which provides integral action and compensates for the dead time in the input/output linear system, and an open-loop state observer. Conditions for robust stability with respect to errors in the dead time and more general linear unstructured multiplicative uncertainties are given. Computer simulations for an example system demonstrate the high controller performance that can be obtained using the proposed method [4].

Gong Xiaofeng et al. presented a proportional integral derivative controller design method based on internal model control that is attractive to industrial users because it has only one tuning parameter. The parameter relates directly to the closed loop speed of response and the robustness of the control loop. For a system with dead time if used as an approximation for the time delay the internal model control controller includes implicitly integral action and has a proportional integral derivative controller structure in cascade with a filter. In their mathematical development Morari-Zafiriou used a first order pade approximation for the time delay in process model by using a non-symmetric second order approximation instead; one can preserve the simple second order form of the controller for their model and not make the structure of the controller complex. In addition significant improvements in model matching and controller tuning can be obtained. Especially for those processes that have significant dead time [7].

Ian G. Horn et al. demonstrated the widely published internal model control proportional-integral-derivative tuning rules provide poor load disturbance suppression for processes in which the desired closed-loop dynamics is significantly faster than the open loop dynamics. The internal model control filter is modified to derive low-order controllers that provide effective disturbance suppression irrespective of the location at which the disturbances enter the closed-loop system [8].

Yongho Lee et al. has explained proportional integral and derivative parameters are obtained for general process models by approximating the feedback form of an internal model control controller with a Maclaurin series in the Laplace variable. These proportional integral and derivative parameters yield closed-loop responses that are closer to the desired responses than those obtained by proportional integral and derivative controllers tuned by other methods. The improvement in closed-loop control performance becomes more prominent as the dead time of the process model increases. A new design method for two degree of freedom controllers is also proposed. Such controllers are essential for unstable processes and provide significantly improved dynamic performance over single degree of freedom controllers for stable processes when the disturbances enter through the process [9].

Syder J et al. has compared a number of proportional integral and derivative and predictive controller strategies to compensate processes modelled in first order lag plus time delay form. The performance and robustness of the resulting compensated systems are evaluated analytically (where appropriate) and in simulation [10].

Sigurd Skogestad et.al. presented analytic tuning rules which are as simple as possible and still result in a good closed-loop behaviour. The starting point has been the internal model control, Proportional, integral, and derivative tuning rules of Rivera, Morari and Skogestad which have achieved widespread industrial acceptance. The integral term has been modified to improve disturbance rejection for integrating processes. Furthermore, rather than deriving separate rules for each transfer function model, we start by approximating the process by a first-order plus delay processes (using the half method) and then use a single tuning rule. This is much simpler and appears to give controller tunings with comparable performance. All the tunings are derived analytically and are thus very suitable for teaching [12].

G.K.I. Mann et.al. has described the time domain proportional integral and derivative analysis includes three types of first order plus time delay (FOPTD) models: (a) zero or negligible time delay,(b) low to medium long time delay and (c) very long time delay. The first part of the analysis proves that the optimum proportional integral and derivative controller for plants having negligible time delay is a proportional integral controller and the corresponding proportional integral terms based on the actuator's capacity and set point overshoot are explicitly derived. For low to medium time delay problems a new proportional integral and derivative tuning scheme is then developed. The proposed tuning rule is capable of accommodating the actuator's saturation and therefore has the ability to select an optimum proportional integral and derivative controller. By using a separate time response analysis a new proportional integral tuning scheme for large normalised time delay is then derived. Numerical studies are made for higher-order processes having monotonic open-loop characteristics. The performance is compared with other commonly available tuning rules. With new tuning rules, better performance is observed and the rules have the capability to cover time delays ranging from zero to any higher value [13].

Dan Chen et al. presented a design method for proportional integral and derivative controllers based on the direct synthesis approach and specification of the desired closed-loop transfer function for disturbances is proposed. Analytical expressions for proportional integral and derivative controllers are derived for several common types of process models including first-order and second-order plus time delay models and an integrator plus time delay model. Although the controllers are designed for disturbance rejection, the set-point responses are usually satisfactory and can be tuned independently via a set-point weighting factor. Nine simulation examples demonstrate that the proposed design method results in very good control for a wide variety of processes including those with integrating and/or nonminimum phase characteristics. The simulations show that the proposed design method provides better disturbance rejection than the standard direct synthesis and internal model control methods when the controllers are tuned to have the same degree of robustness [15].

Sigurd Skogestad et al. presented rules for proportional integral and derivative controller tuning that are simple and still result in good closed loop behaviour. The starting point has been the internal model control proportional integral and derivative tuning rues that have achieved widespread industrial acceptance. The rule for integral term has been modified to improve the disturbance rejection for integrating processes.

Furthermore, rather than deriving separate rules for each transfer function model, there is just a single tuning rule for a first order or second order time delay model. Simple analytic rules for model reduction are presented to obtain a model in this form, including the ‘half rule’ for effective time delay [17].

Qing-Guo Wang et.al. has been explained in this paper about newly developed control methods for unstable processes with time delays are reviewed. Seven existing controller design methods are evaluated regarding their applicability’s, control performance and robustness. The comparison is shown by simulations results and data statistics [20].

Kiam Heong Ang et.al. presented designing and tuning a proportional integral derivative controller appears to be conceptually intuitive, but can be hard in practice, if multiple (and often conflicting) objectives such as short transient and high stability are to be achieved. Usually initial designs obtained by all means need to be adjusted repeatedly through computer simulations until the closed-loop system performs or compromises as desired. This stimulates the development of intelligent tools that can assist engineers to achieve the best overall proportional integral and derivative control for the entire operating envelope. This development has further led to the incorporation of some advanced tuning algorithms into proportional integral and derivative hardware modules. Corresponding to these developments, this paper presents a modern overview of functionalities and tuning methods in patents, software packages and commercial hardware modules. It is seen that many proportional integral and derivative variants have been developed in order to improve transient performance, but standardising and modularisingproportional integral proportional integral and derivative control are desired, although challenging. The inclusion of system identification and “intelligent” techniques in software based proportional integral and derivative systems helps automate the entire design and tuning process to a useful degree. This should also assist future development of plug-and-play proportional integral and derivative controllers that are widely applicable and can be set up easily and operate optimally for enhanced productivity, improved quality and reduced maintenance requirements [22].

Wen Tan et.al. described a criteria based on disturbance rejection and system robustness are proposed to assess the performance of proportional integral and derivative controllers. A simple robustness measure is defined and the integral gains of the proportional integral and derivative controllers are shown to be a good measure for disturbance rejection. An analysis of some well-known Proportional proportional integral and derivative tuning formulas reveals that the robustness measure should lie between 3 and 5 to have a good compromise between performance and robustness [26].

M. Shamsuzzoha et.al. has demonstrate the internal model control- proportional integral and derivative tuning rules for good set-point tracking but sluggish disturbance rejection, which becomes severe when a process has a small time-delay/time-constant ratio. In this study, an optimal internal model control filter structure is proposed for several representative process models to design a proportional integral derivative controller that produces an improved disturbance rejection response. The simulation studies of several process models show that the proposed design method provides better disturbance rejection for lag-time dominant processes, when the various controllers are all tuned to have the same degree of robustness according to the measure of maximum sensitivity. The robustness analysis is conducted by inserting a perturbation in each of the process parameters simultaneously, with the results demonstrating the robustness of the proposed controller design with parameter uncertainty. A closed-loop time constant ì guideline is also proposed for several process models to cover a wide range of θ/τ ratios [27].

Truong Nguyen Luan Vu et.al. presented a new method of designing multi-loop proportional integral and derivative controllers is presented in this paper. By using the generalized Internal model control- proportional integral and derivative method for multi-loop systems, the optimization problem involved in finding the proportional integral and derivative parameters is efficiently simplified to find the optimum closed-loop time constant in a reduced search space. A weighted sum Mp criterion is proposed as a performance cost function to cope with both the performance and robustness of a multi-loop control system. Several illustrative examples are included to demonstrate the improved performance of the multi-loop proportional integral and derivative controllers obtained by the proposed design method [28].

Michel Fliess et.al. presented an intelligent proportional integral and derivative controller or internal model control- proportional integral and derivative controllers are proportional integral and derivative controllers where the unknown parts of the plant, which might be highly nonlinear and/or time-varying are taken into account without any modelling procedure. Our main tool is an online numerical differentiator which is based on easily implementable fast estimation and identification techniques. Several numerical experiments demonstrate the efficiency of our method when compared to more classic proportional integral and derivative regulators [29].

R. Farkh et al. presented in this paper about the control of time delay system by proportional-integral (PI) controller. By Using the Hermite - Biehler theorem, which is applicable to quasi-polynomials, we seek a stability region of the controller for first order delay systems. The essence of this work resides in the extension of this approach to second order delay system, in the determination of its stability region and the computation of the proportional integral optimum parameters. We have used the genetic algorithms to lead the complexity of the optimization problem [30].

Tao Liu et.al. demonstrate a paper based on the internal model control structure, an iterative learning control scheme is proposed for batch processes with model uncertainties including time delay mismatch. An important merit is that the internal model control design for the initial run of the proposed control scheme is independent of the subsequent ILC for realization of perfect tracking. Sufficient conditions to guarantee the convergence of ILC are derived. To facilitate the controller design a unified controller form is proposed for implementation of both internal model control and ILC in the proposed control scheme. Robust tuning constraints of the unified controller are derived in terms of the process uncertainties described in a multiplicative form. To deal with process uncertainties, the unified controller can be monotonically tuned to meet the compromise between tracking performance and control system robust stability. Illustrative examples from the recent literature are performed to demonstrate the effectiveness and merits of the proposed control scheme [31].

Susmita Das et.al. has explained about proportional integral derivative tuning approach using traditional Ziegler-Nichols tuning method with the help of simulation aspects. The most important reason behind this proportional integral derivative tuning approach is due to its simple control structure and satisfactory results. Nowadays there are various optimization techniques like Particle Swarm Optimization (PSO), Bacterial Forging Optimization (BFO), Genetic Algorithm (GA) etc used for distributed optimization and tuning of various systems. For proportional integral derivative tuning software tools are also used somewhere in which programming has been done previously. But here Z-N tuning rule is chosen as it is the mother of all the globally accepted modern Optimization Algorithms and easy to implement during matlab simulation. In this tuning approach Z-N's First Method is used which is efficient in tuning stable systems. The Algorithm and Flowchart study of the Z-N tuning rule is also incorporated. The flowchart defines the sequential statements and functions executed during simulation and also show the transfer of function calls. The algorithm makes the coding efficient and prevents runtime error. The coding is completely done using matlab and for its execution minimum requirement version is matlab R2010a. The matlab coding consists of two parts i.e. Routh-Hurwitz coding to determine whether the system is stable or unstable and the code of Z-N tuning rule that performs the tuning of the systems provided by the user. The tuning code runs with the help of two functions, Ziegler and WRITEPID. This tuning approach would be advantageous for the future industries as proportional integral derivative is used for industry related work and projects with the help of two functions, Ziegler and WRITEPID. This tuning approach would be advantageous for the future industries as proportional integral derivative is used for industry related work and projects [33].

V. Kongratana et.al. has presented about performance speed control design of proportional integral derivative controllers for a torsional vibration system based on internal model control. For the model of the torsional vibration suppression in two-mass system which includes an internal model control filter must be selected properly so that the designed internal model control controllers can be approximated as proportional integral derivative controller by using Maclaurin approximation, are increasingly required in embedded system implemented on microcontrollers, oriented controlled ac motor drive system torsional vibration mechanical system, the characteristics of speed controller and typical internal model control - proportional integral derivative speed controller. The simulation and experiment results verify the applicability and satisfied performance of the proposed control system [34].

QIN Gang et.al. has described in allusion to unmanned vehicle steering control of the brushless DC motor control system, traditional proportional integral derivative controller parameter adjustment complex, weak ability to adapt to the environment and other issues, on the basis of the analysis of internal model control and classical proportional integral derivative control internal corresponding relationship, comprehensive its advantages, The design uses a brushless DC motor in the steering control system for unmanned vehicles based on the internal model proportional integral derivative controller for speed. Based on the build object theoretical model, online simulation controller show that, for the design objects, based on the internal model proportional integral derivative controller whether the system step response or disturbance tracking control effect can reach the classic proportional integral derivative control requirements, also reduces the complexity and randomness of the design parameters [35].

CHAPTER 3
TUNING OF PID CONTROLLER

3.1 Basic Introduction

For the control system to be exhibits desired property parameters of the controller need to be adjusted. It is called the tuning. Proportional integral derivative controllers used in many of the industries. Most of these controllers were analog but today's controllers use digital signals and computers. The parameters of the controller can be explicitly determined when a mathematical model of a system is available. The parameters determined experimentally when a mathematical model is unavailable. The controller parameters produce the desired output determined by controller. Controller tuning allows optimization of a process and minimizes the error between the variable of the process and its set point.

The various types of controller tuning methods include the trial and error method and process reaction curve methods. The most common classical controller tuning methods are the Ziegler-Nichols and Cohen-Coon methods. These methods are often used when the mathematical model of the system is not available. The Ziegler-Nichols method can be used for both closed and open loop systems while Cohen-Coon is typically used for open loop systems. A closed-loop control system is a system which uses feedback control. In an open-loop system the output is not compared to the input.

The equation of the proportional integral derivative controller is shown below

$$u(t) = Kp \left[e(t) + 1 / Ti \int_{o}^{t} e(t')\, dt' + Td \left(de(t) / d(t) \right) + b \right. \quad (3.1)$$

u is the control signal.
e is the difference between the current value and the set point.
Kc is the gain for a proportional controller.
Ti is the parameter that scales the integral controller.
Td is the parameter that scales the derivative controller.
t is the time taken for error measurement.
b is the set point value of the signal, also known as bias or offset

3.2 Ziegler-Nichols Rules for tuning Proportional Integral Derivative Controller

A proportional integral derivative controller has three tuning parameters. If these are adjusted in an ad hoc fashion then it may take a while to get a satisfactory performance of controller. So the two tuning methods were proposed by Ziegler and Nichols in 1942 [1] and have been widely utilized either in the original form or in modified forms [6]. First method is referred to as Ziegler–Nichols ultimate sensitivity method. To determine the parameters as given in Table 3.1 using the data Kcr and Tcr obtained from the ultimate sensitivity test. The second method is referred to as Ziegler–Nichols step response method is to assume the model first order plus delay time and to determine the parameters of the proportional integral derivative controller.

Type of controller	Kp	τi	τd
P	0.5Kcr	∞	0
PI	0.45Kcr	0.833 Tcr	0
PID	0.6Kcr	0.5 Tcr	0.125 Tcr

Table 3.1: Ziegler-Nichols ultimate sensitivity test [32].

3.2.1 Tuning Rules for First-Order + Dead Time Processes

The previous tuning rules were based on tests that forced a process into a continuous oscillation. Due to this the system is forced to the edge of instability and it may take a while to iteratively adjust the controller to obtain a continuous oscillation. The tuning rules explained below based on the process models which have been obtained through open loop step tests.

i. Ziegler-Nichols Open Loop Method.
ii. Cohen-Coon Parameters.

a. Ziegler-Nichols Open Loop Method

Ziegler and Nichols also proposed tuning parameters for a process that has been identified as integrator + time-delay based on an open-loop process step response.

$$Gp(s) = Ke^{-\theta s} / s \qquad (3.2)$$

The first-order + time-delay processes have a maximum slope of k = kp / tp at t = q for a unit step input change these same rules can be used for first-order + time-delay processes.

$$Gp(s) = Ke^{-\theta s} / \tau ps + 1 \qquad (3.3)$$

The recommended tuning parameters give roughly quarter wave damping are shown in Table 3.2. With a low time delay / time constant ratio a potential problem occurs for the systems. It causes the proportional gain to become very large. So the integral time tends to be low causing the oscillatory behaviour.

Controller type	Kc	τi	τd
P-only	$\frac{1}{K\theta}$ or $\frac{\tau p}{Kp\theta}$	------	-------
PI	$\frac{.9}{K\theta}$ or $\frac{.9\tau p}{Kp\theta}$	3.3θ	-------
PID	$\frac{1.2}{K\theta}$ or $\frac{1.2\tau p}{Kp\theta}$	2θ	0.5θ

Table 3.2 Ziegler-Nichols step response method ($K\theta \neq 0$) [19]

The closed-loop Ziegler-Nichols method consists of the following steps.

i. With P-only closed-loop control increase the magnitude of the proportional gain until the closed-loop is in a continuous oscillation. For slightly larger values of controller gain, the closed-loop system is unstable, while for slightly lower values the system is stable.

ii. The value of controller proportional gain that causes the continuous oscillation is called the critical or ultimate gain Kcr. The peak-to-peak period time between successive peaks in the continuously oscillating process output is called the critical or ultimate period Tcr.

iii. Depending on the controller chosen, P, PI, or PID, use the values in Table 3.1 for the tuning parameters based on the critical gain and period [19].

Frequency-domain stability analysis tells that the above way of applying the Ziegler–Nichols step response method to processes with self-regulation tends to set the parameters on the safe side. The actual gain and phase margins become larger than the values expected in the case of integrating processes.

These methods to determine proportional integral derivative parameter using empirical formula as well as several other tuning methods developed on the same principle often referred to as classical tuning methods. Some of the other classical tuning methods are Chien–Hrones–Reswick formula, Cohen–Coon formula, refined Ziegler–Nichols tuning, Wang–Juang–Chan formula.

Disadvantages

The classical tuning methods explained above have the following features

i. The process is assumed implicitly in the case of Ziegler–Nichols ultimate sensitivity method or explicitly in the case of Ziegler–Nichols step response method to be modelled by the simple transfer function.

ii. The optimal values of the proportional integral derivative parameters are given by formula of the process parameters that are determined directly and uniquely from experimental data.

The first feature is a weakness of these classical methods in the sense that the applicable processes are limited or the claimed optimal values are not necessarily and are sometimes fairly far from the true optimal in practical situations where the transfer function is nothing but an approximation of the real process characteristics. When the pure delay L of the process is very short or very long means outside the range $0.05 \leq L/T \leq 1.0$ [32]. So there is no room to improve the results by making use of more detailed information about the process which is obtainable from theoretical study and accurate measurement.

To overcome these weaknesses of the classical methods many attempts have been made. To develop sophisticated methods which use as the basis of tuning the shape of the frequency response of the return ratio, poles and zeros of the closed-loop transfer function, time-domain performance indices such as ISE or frequency-domain performance indices many theoretical considerations have been used.

b. Cohen-Coon Method

This method is developed by Cohen and Coon in 1953. The main objective of this method is load disturbance rejection[2]. The method is based on the First order plus time delay process model shown below.

$$G(s) = \frac{Kp}{1 + sT} e\text{-}st \qquad (3.4)$$

Kp is the static gain of the process

T the time-constant and

τ is the delay.

The equation of model (3.4) needs to characterize the process dynamics adequately so the process should be stable for the method to be applicable. The method attempts to position the dominant poles so that a quarter amplitude decay ratio is achieved. In the proportional integral or proportional integral derivative controller the integral gain ki = K / Ti is maximized which corresponds to the minimization of the integral of error due to a unit step load disturbance [25]. Cohen and Coon derived the controller parameters based on the FOTD process model and analytical and numerical computations. A set of tuning parameters was empirically developed to yield a closed loop response with decay ratio similar to Ziegler-Nichols methods. The controller parameters are given in Table 3.3, where $\beta = Kp\tau / T$ is gain and $\kappa = \tau / (\tau + T)$.

Controller	K	τi	τd
P	$\frac{1}{\beta}\left(1 + \frac{0.35K}{1-K}\right)$		
PI	$\frac{0.9}{\beta}\left(1 + \frac{0.092K}{1-K}\right)$	$\frac{3.3 - 3.0K}{1 + 1.2K}\tau$	
PD	$\frac{1.24}{\beta}\left(1 + \frac{0.13K}{1-K}\right)$		$\frac{0.27 - 0.36K}{1 - 0.87K}\tau$
PID	$\frac{1.35}{\beta}\left(1 + \frac{0.18K}{1-K}\right)$	$\frac{2.5 - 2.0K}{1 - 0.39K}\tau$	$\frac{0.37 - 0.37K}{1 - 0.81K}\tau$

Table 3.3: Proportional integral controller parameters according to Cohen –Coon method [25]

is the relative dead time. The Cohen-Coon parameters do not tend to be very robust i.e. a small change in the process parameters can cause the closed loop system to become unstable [19].

3.3 Direct Synthesis

The performance or stability of the closed-loop system from the closed-loop transfer Function is given by

$$y(s) = (Gp(s)\ Gc(s)\ \ r(s)) / (1 + Gp(s)\ Gc(s)) \tag{3.5}$$

$$y(s) = Gcl(s) / (Gp(s)\ (1 – Gcl(s))) \tag{3.6}$$

The relationship between any external signal such as a setpoint change r(s) and any other signal on the control block diagram can be found. It is important to analyze the manipulated variable action required for a setpoint change to make certain that it is not too rapid or that it does not violate constraints. The effect of manipulated variable action is given by

$$u(s) = Gc(s)\, r(s) / (1 + Gp(s)\, Gc(s)) \qquad (3.7)$$

The The direct synthesis procedure specifying the desired closed-loop transfer function first-order response, second-order under damped. The feedback controller and considering the manipulated variable response tested by simulation is given by Gcl(s) using Equation (3.6).

So it is not limited by the desired closed loop response if the system is minimum phase process does not have RHP zeros or time delays [19].

3.3.1 Direct Synthesis for Minimum-Phase Processes

To specify a desired closed loop response the characteristics of a first-order response is given by

$$Gcl(s) = 1 / (\lambda s + 1) \qquad (3.8)$$

For a specified first-order response, there is only one tuning parameter λ. A closed-loop gain of 1 means the process output to equal the setpoint as the closed-loop system goes to a new steady state. The small values of λ results in fast responses and large values result in slow responses [19].

3.3.2 Direct Synthesis for Non Minimum-Phase Processes

For nonminimum-phase processes the processes have time delays or RHP zeros. The general technique remains the same for these processes. There is a restriction on the type of closed-loop response that can be specified [19].

3.4 AMIGO Tuning Rules

The Approximate M-constrained Integral Gain Optimization AMIGO tuning rules [21, 25] proposed by Astrom and Hagglund. Its represent the recently developed tuning rules for the classical PID controller. These tuning rules are derived using the step response test approach for a batch of different process models stable and marginally stable in the spirit of the work done by Ziegler and Nichols. In the test batch all the stable processes are first characterized with the simple FOTD model. The use of techniques like robust loop shaping and thorough analysis of robustness, performance and closed-loop system properties described in and finally give the following tuning rules for stable processes [21, 25].

$$K = \frac{1}{Kp} (0.2 + 0.45 + (T/\tau)) ; \quad Ti = \frac{0.8T + 0.4\tau}{0.1T + \tau} \tau ; \quad Td = \frac{0.5T\tau}{T + 0.3\tau} \qquad (3.8)$$

This tuning rule might be conservative for lag dominated T >> τ processes. To characterize the plant the largest time constant of the plant maps into the time constant of the FOTD model but in the delay parameter of the FOTD model the smaller time constants may be included. So the delay of the FOTD model may become unnecessarily large. The modelling and control design procedure becomes less simple if better modelling of the process and tuning rules based on a more complicated process model but it could improve the performance of the system. The use of the step experiment as the basis of modelling restricts the complexity of the process model to that of FOTD. Higher order models require more advanced identification procedures. So AMIGO tuning defines values for the set-point weights and the measurement filter time-constant instead of the controller gains. The control algorithm is given below

$$u(t) = Kp(byr(t) - yf(t)) + Ki \int_{o}^{t} (yr(\alpha) - yf(\alpha))\, d\alpha + Kd(c\, (dyr(t) / dt) - (dyf(t) / dt) \qquad (3.9)$$

Parameters b and c are the set-point weights

yf is the measured and filtered process variable

The Laplace transform of yf(t) is given by

$$Yf(s) = Gf(s)\, Y(s) \qquad (3.10)$$

$$Gf(s) = 1 / (1 + sTf)n \qquad (3.11)$$

Gf(s) is the measurement filter with a time-constant Tf. The order of the filter n is typically has value of one or two. The tuning rules for set-point weights and the filter time constant are given by

$$K = \frac{\tau}{\tau + T}; \quad b = \begin{cases} 0, & K \leq 0.5 \\ 1, & K > 0.5 \end{cases}; \quad c = 0; \quad Tf = \begin{cases} 0.05 / wgc, & K \leq 0.2 \\ 0.1\,\tau, & k > 0.2 \end{cases} \tag{3.12}$$

gc ω is the gain crossover frequency.

The above choice of Tf reduces the phase margin of the system by 0.1 radian [21]. The phase margin and the jitter margin are intuitively coupled. So there is a good motivation for investigating the relationship of Tf and the jitter margin when considering the use of AMIGO rules for NCS. The Tf can be tuned based on the jitter margin requirement which leads to tuning rules. The desired jitter margin can be given as an input parameter to the rules.

In AMIGO tuning the setpoint weight c = 0. Because in the CT case the derivative of a step-like reference signal is infinite at the time the step is applied. Unit steps are frequently used in the simulations as the reference and the set-point weight c needs to be zero. The filter time constant is calculated based on the gain crossover frequency which is the lowest frequency where the magnitude of the open-loop system becomes less than one in the case $K \leq 0.2$. The AMIGO tuning also considers integrating processes, and the tuning rules for them are presented separately. The process model used is the integrator plus delay IPD.

$$G(s) = (Kv\, e^{-s\tau}) / s \tag{3.13}$$

Kv is the velocity gain.

$$K = 0.45 / Kv \,;\; Ti = 8\tau \,;\; Td = 0.5\tau \tag{3.14}$$

3.5 Internal Model Control Tuning of Proportional Integral Derivative controllers

Internal model control IMC is a model-based control method. The internal model control method can also be used as a tuning method for the proportional integral derivative controller. Generally, the method is applicable for systems with constant delays but the internal model control method is also applied for varying time-delay systems. Figure 3.1 represents the internal model control principle. In the figure

Gp(s) is the process controlled

Q is the IMC controller

G̃p(s) is the process model

d(s) is the disturbance

y is the process output

ỹ is the process model output

r is the set point

The model output error $y - \tilde{y}$ is subtracted from the reference signal and fed into the internal model control controller which calculates the control signal.

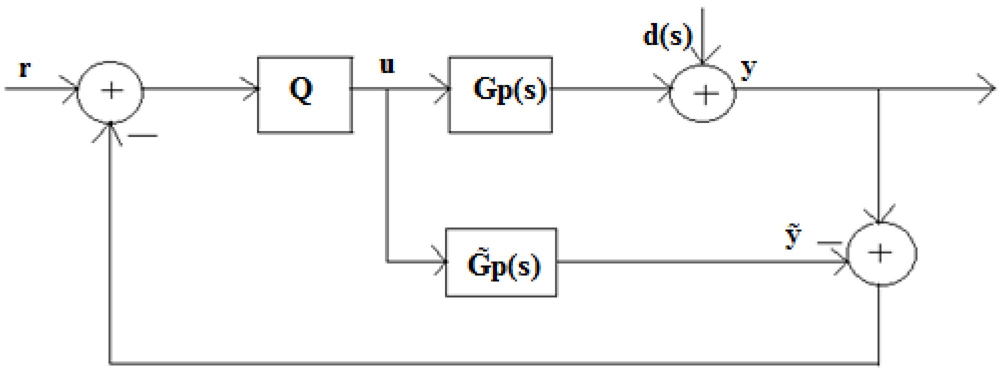

Figure 3.1: IMC modified structure [3]

A internal model control controller *Q*(*s*) is calculated so that the process model is first divided into two parts

$$\tilde{G}p(s) = \tilde{G}p+ (s) \ \tilde{G}p- (s) \qquad (3.15)$$

G̃p+ (s) is the non-invertible part of the model including all unstable zeros and delays. The rest of the model is included in G̃p- (s). The controller is given as

$$Q(s) = \tilde{G}_{-}(s)^{-1} f(s) \qquad (3.16)$$

where f is a low-pass filter transfer function of order *n* given as

$$f(s) = \frac{1}{(1 + s\,\lambda_{IMC})^n} \qquad (3.17)$$

The low-pass filter is required in order to have a causal controller. The λIMC is the tuning parameter of the internal model control method. The value of λIMC has a significant effect on the performance and robustness of the controlled system. There is a trade-off a very fast and simultaneously very robust tuning is generally difficult to achieve. In varying time-delay systems where robustness with respect to delay variance plays a crucial role the tuning of λIMC turns out to be crucial. The dependency between the jitter margin the control system performance. So the λIMC parameter is further discussed where control is used in the NCS setup.

When implementing the internal model control controller, it is useful to recognize the dependency between the internal model control controller *Q* in Figure 3.1 and the controller in the classical feedback loop. The internal model control law in the classical control loop is given by

$$Gc(s) = \frac{Q(s)}{1 - \tilde{G}(s)\,Q(s)} \qquad (3.18)$$

The process delays must be approximated with linear transfer functions in order to be able to calculate the controller if the controller is used. A constant delay of τ seconds corresponds to an exponential function $e^{-\tau s}$ in the Laplace domain, and the delay can be approximated with the Taylor series expansion or the first order Padé approximation

$$e^{-\tau s} = \frac{(1 - s\,\tau / 2)}{(1 - s\,\tau / 2)} \qquad (3.19)$$

The internal model control design often yields high order controllers under certain assumptions. It is possible to obtain the proportional integral control structure from the internal model control design and thus get the tuning parameters for a regular proportional internal control controller. Consider the FOTD process model. Using the internal model control design and the first order Taylor series expansion $e^{-s\tau} \approx 1 - s\tau$ with n = 1 order of the low-pass filter the controller C becomes [6].

$$CPI(s) = \frac{1 + sT}{Kps\,(\lambda IMC + \tau)} = \frac{T}{Kp\,(\lambda IMC + \tau)} = (1 + 1 / sT) \qquad (3.20)$$

The proportional integral controller structure with parameters is given below

$$K = \frac{T}{Kp\,(\lambda IMC + \tau)} = \quad Ti = T \qquad (3.21)$$

$$kp = \frac{(1 + 1 / sT)}{Kp\,(\lambda IMC + \tau)}\ ;\ ki = \frac{1}{Kp\,(\lambda IMC + \tau)} \qquad (3.22)$$

If the Padé approximation of the delay is used the controller C becomes

$$CPID\,(s) = \frac{(1 + sT)\,(1 + 1 / s\,\tau / 2)}{Kps\,(s\,\lambda IMC / 2 + \lambda IMC + \tau)} \qquad (3.23)$$

$$CPID\,(s) = \frac{(1 + sT)\,(1 + 1 / s\,\tau / 2)}{Kps\,(\lambda IMC + \tau)} \qquad (3.24)$$

a proportional integral control controller. This form of the proportional integral control controller is actually the interacting controller or the analog algorithm [18]. Comparing (3.20) and (3.22) reveals that

$$CPID(s) = \underbrace{\frac{T}{K_p s(\lambda IMC + \tau)}}_{CPI(s)} (1 + 1/sT)(1 + s\tau/2) \quad (3.25)$$

$$= \underbrace{\frac{T}{K_p(\lambda IMC + \tau)}}_{kp}(1 + \tau/2) + \underbrace{\frac{1}{K_p(\lambda IMC + \tau)\, s}}_{ki} + \underbrace{\frac{T\tau s}{2K_p(\lambda IMC + \tau)}}_{kd} \quad (3.26)$$

$$K = \frac{T}{K_p(\lambda IMC + \tau)}(1 + \tau/2T); \quad Ti = T + \tau/2; \quad Td = \frac{T\tau}{2T + \tau} \quad (3.27)$$

3.5.1 The Internal Model Control Based Proportional Integral Derivative Control Design Procedure

The following steps are used in the internal model control based proportional integral derivative control system design

1. First of all controller transfer function q(s) has to be find out which includes a filter f(s) to make q(s) semiproper or to give it derivative action the order of the numerator of q(s) is one order greater that the denominator of q(s). It is a major difference from the internal model control procedure. In order to find an equivalent proportional integral derivative controller q(s) needs to be improper. For integrating or unstable processes or for better disturbance rejection a filter with the following form will often be used

$$f(s) = \lambda s + 1 / (\lambda s + 1)n \quad (3.28)$$

2. From this the equivalent standard feedback controller using the transformation is given by

$$Gc(s) = Q(s) / 1 - \tilde{G}p(s)\, Q(s) \quad (3.29)$$

3. The equation (3.29) needs to be shown in proportional integral derivative form and then evaluate kc, τi, τd. Sometimes this procedure results in an ideal proportional integral derivative controller cascaded with a first-order filter with a filter time constant (τf).

$$Gc(s) = kc\,[(\tau i\ \tau D s^2 + \tau i s + 1) / \tau i s] * [1 / \tau f s + 1] \qquad (3.30)$$

4. For both the perfect model case and cases with model mismatch closed-loop simulations has to be performed. Adjust λ considering a tradeoff between performance and robustness sensitivity to model error. Initial values for λ will be around 1/3 to 1/2 the dominant time constant [19].

3.5.2 Internal Model Control-Based Feedback Design for Processes with a Time Delay

Some approximation to be made for the dead time for proportional integral derivative equivalent form for processes with a time delay we must make. The internal model control-based proportional integral derivative procedure is only done to yield a proportional integral derivative type controller. So either a first-order Padé approximation for dead time or neglect dead time entirely and use the first-order transfer function results.

First-Order + Dead Time

The first-order + dead time is the most common representation of chemical process dynamics. The proportional integral derivative equivalent form developed is useful for a large number of process control loops. The following steps are used in the internal model control based proportional integral derivative design for first order plus dead time processes.

The process is given by

$$Gp(s) = kp\ e^{-\theta s} / \tau p\ s + 1 \qquad (3.31)$$

1. The first order approximation for the dead time is given by

$$e^{-\theta s} = (-0.5\theta s + 1) / (0.5\theta s + 1) \qquad (3.32)$$

$$G_p(s) = \frac{K_p\, e^{-\theta s}}{\tau_p s + 1} = \frac{k_p(-0.5\theta s + 1)}{(\tau_p s + 1)(0.5\theta s + 1)} \qquad (3.33)$$

2. Factor out the noninvertible elements to avoid the bad part all-pass

$$\tilde{G}_{p-}(s) = k_p / (\tau_p s + 1)(0.5\theta s + 1) \qquad (3.34)$$

$$\tilde{G}_{p+}(s) = (-0.5\theta s + 1) \qquad (3.35)$$

3. The idealized controller is then given by

$$\tilde{Q}(s) = (\tau_p s + 1)(0.5\theta s + 1) / k_p \qquad (3.36)$$

4. The filter f(s) is added to make the Q(s) proper. But Q(s) will be make semiproper to get the proportional integral derivative controller. The derivative option will be used to allow the numerator of q(s) to be one order higher than the denominator. It is done only to obtain an ideal proportional integral derivative controller.

$$Q(s) = \tilde{Q}(s)\ f(s) = (1 / \tilde{G}_{p-}(s))\, f(s)$$

$$= (\tau_p s + 1)(0.5\theta s + 1)\ (1) / k_p(\lambda s + 1) \qquad (3.37)$$

The proportional integral derivative equivalent can be given as

$$G_c(s) = Q(s) / 1 - \tilde{G}_p(s)\, Q(s) = \tilde{Q}(s)\ f(s)\ / 1 - \tilde{G}_p(s)\, f(s)\, Q(s) \qquad (3.38)$$

$$G_c(s) = \tilde{Q}(s)\ f(s)\ / 1 - \tilde{G}_{p-}(s)\, \tilde{G}_{p+}(s)\, (1 / \tilde{G}_{p-}(s))\, f(s)$$

$$= \tilde{Q}(s)\ f(s)\ / 1 - \tilde{G}_{p+}(s)\, f(s)$$

$$= \frac{1}{kp} \; \frac{(\tau p\, s + 1)\,(0.5\theta s + 1)}{(\lambda + 0.5\theta s)\; s} \tag{3.39}$$

$$Gc(s) = \frac{1}{kp} \; \frac{0.5\, \tau p \theta s^2 + (\tau p + 0.5\theta)\, s + 1}{(\lambda + 0.5\theta s)\; s} \tag{3.40}$$

Multiply equation (3.40) by $(\tau p + 0.5) / (\theta/\tau p + 0.5\theta)$ PID parameters can be evaluated as shown below

$$Kc = (\tau p + 0.5\theta) / kp\,(\lambda + 0.5\theta) \tag{3.41}$$

$$\tau i = \tau p + 0.5\theta \tag{3.42}$$

$$\tau D = (\tau p\theta) / (2\tau p + \theta)s \tag{3.43}$$

The internal model control based proportional integral derivative controller design procedure has resulted in a proportional integral derivative controller when the process is first-order + dead time. A Padé approximation for dead time was used in this development meaning that the filter factor (λ) cannot be made arbitrarily small. So there will be performance limitations to the internal model control based proportional integral derivative strategy that do not occur in the internal model control strategy. Rivera et.al. (1986) recommend that $\lambda > 0.8\theta$ because of the model uncertainty due to the Padé approximation. The use of an all-pass in the factorization will lead to a proportional integral derivative controller in series with a first-order lag. The parameters in this case are shown as the first entry in Table 3.4. Morari and Zafiriou (1989) recommend $\lambda > 0.25\theta$ for the PID + lag formulation. The third and fourth entries neglect the time delay in forming the PI controller [19]

	Gp(s)	kc	τi	τd	τf	Notes
A	$\frac{Kp\ e^{-\theta s}}{\tau ps + 1}$	$\frac{\tau p + \theta/2}{skp(\theta + \lambda)}$	$\tau p + \theta/2$	$\frac{\tau p\theta}{2\tau p + \theta}$	$\frac{\lambda\theta}{2(\lambda + \theta)}$	1
B	$\frac{Kp\ e^{-\theta s}}{\tau ps + 1}$	$\frac{\tau p + \theta/2}{kp(\theta/2 + \lambda)}$	$\tau p + \theta/2$	$\frac{\tau p\theta}{2\tau p + \theta}$		2
C	$\frac{Kp\ e^{-\theta s}}{\tau ps + 1}$	$\frac{\tau p}{kp\lambda}$	τp			3
D	$\frac{Kp\ e^{-\theta s}}{\tau ps + 1}$	$\frac{\tau p + \theta/2}{kp\lambda}$	$\tau p + \theta/2$			4
E	$\frac{K\ e^{-\theta s}}{s}$	$\frac{2\lambda + \theta}{K(\theta + \lambda)^2}$	$2\lambda + \theta$			5
F	$\frac{K\ e^{-\theta s}}{s}$	$\frac{2}{K(\theta/2 + \lambda)}$	$2\lambda + \theta$	$\frac{\lambda\theta + \theta^2/4}{2\lambda + \theta}$		6
G	$K\ e^{-\theta s}$	$\frac{\theta}{K(2\lambda + \theta)}$	$\theta/2$			7
H	$K\ e^{-\theta s}$	$\frac{\theta}{K(4\lambda + \theta)}$	$\theta/2$	$\theta/6$	$\frac{2\lambda^2 + \theta^2/6}{4\lambda + \theta}$	8

Table 3.4: Proportional integral derivative Tuning Parameters for Stable Time-Delay Processes[19]

Integrator + Dead Time

For processes where the time constant is dominant, the step response behaviour can be approximated as integrator + dead time as characterized by the following transfer function.

$$Gp(s) = K\, e^{-\theta s} / s \qquad (3.44)$$

A Taylor series approximation for dead time is used. Also, the special filter form for integrating systems is used [19].

$$e^{-\theta s} = -\theta s + 1 \qquad (3.45)$$

$$Gp(s) = k(-\theta s + 1) / s \;= (k / s)\,(-\theta s + 1) \qquad (3.46)$$

$$Q(s) = (s / k).\ ((\lambda s + 1) / (\lambda s + 1)^2) \qquad (3.47)$$

By using internal model control based proportional integral derivative procedure

$$Gc(s) = Q(s) / 1 - \tilde{G}p\,(s)\, Q(s) \qquad (3.48)$$

A proportional integral controller results with the following parameters

$$kc = 2\lambda + \theta / k(\lambda + \theta)^2 \qquad (3.49)$$

$$\tau i = 2\lambda + \theta$$

Gain + Dead Time

For processes where the time delay is dominant the step response behavior can be approximated as gain + dead time as characterized by the following transfer function.

$$Gp(s) = K\, e^{-\theta s} \qquad (3.50)$$

Using a second-order Padé approximation for the time delay [19]

$$e^{-\theta s} = \frac{\theta^2 s^2 / 12 - \theta s / 2 + 1}{\theta^2 s^2 / 12 + \theta s / 2 + 1} \qquad (3.51)$$

$$G_p(s) = k\frac{\theta^2 s^2 / 12 - \theta s / 2 + 1}{\theta^2 s^2 / 12 + \theta s / 2 + 1} = \frac{k}{\theta^2 s^2 / 12 + \theta s / 2 + 1}(\theta^2 s^2 / 12 - \theta s / 2 + 1) \quad (3.52)$$

The PID plus filter controller results with

$$\begin{aligned} k_c &= \theta / (4\lambda + \theta) \\ \tau_i &= \theta / 2 \\ \tau_d &= \theta / 6 \\ \tau_F &= (2\lambda^2 - \theta/6) / (4\lambda + \theta) \end{aligned} \quad (3.53)$$

but $\lambda > \theta / \sqrt{2}$.

CHAPTER4

SIMULATION AND RESULTS

4.1System Implementation

The internal model control based proportional integral derivative controller design with time delay is implemented using matlab. The version of matlab used here is 7.13.0.564 (R20011b). The standard matlab package is useful for linear systems analysis. The version of simulink used is 7.8 (R2011b). The simulink is far more useful for control system simulation. simulink enables the rapid construction and simulation of control block diagrams.

4.2 Ideal Internal Model Control based Proportional Integral Derivative Controller

The actual process transfer function is never known exactly. So it is necessary to use two transfer function representations of the process. So one is considered as process or plant which is never known exactly and the second is considered as process model which is known exactly. In internal model controller process model is kept in parallel with the actual process. The ideal internal model control based proportional integral derivative controller means the model is perfect and there is no disturbance and delay. So the feedback is also nil. The equation which tells that the model is perfect is given below i.e open loop system.

$$Gp(s) = \tilde{G}p(s) \tag{4.1}$$

$$d(s) = 0 \tag{4.2}$$

Gp(s) is the process transfer function.

$\tilde{G}p(s)$ is the process model.

d(s) is the disturbance.

4.2.1 Simulation of Ideal Internal Model Control Based Proportional Integral Derivative Design

The internal model controller provides a transparent frame work for control system design and tuning. For simulation of ideal internal model control based proportional integral derivative controller. The first order transfer function of the process has been adopted as a reference [3.6]. The derivation to calculate the parameters of ideal internal model control based proportional integral derivative controller is given below.

$$Gp(s) = kp / (\tau ps + 1)$$

Gp(s) is the transfer function of the process

$$Gp(s) = 10 / (8s + 1) \tag{4.3}$$

The ideal internal model control controller transfer function Q(s) which includes the filter f(s) to make a Q(s) semiproper is given below

$$Q(s) = Gp\text{-}1(s)\ f(s) \tag{4.4}$$

$$f(s) = 1 / (\lambda s + 1) \tag{4.5}$$

$$Q(s) = ((8s + 1) / 10) * (1 / \lambda s + 1) \tag{4.6}$$

λ is the tuning parameter of the filter f(s)

Take the value of λ as 0.533, which is practically one third of one fifth of time constant and put it in equation (4.6) to get the value of ideal internal model control controller Q(s). The equation becomes

$$Q(s) = ((8s + 1) / 10) * (1 / 0.53s + 1)$$

$$Q(s) = (8s + 1) / (5.33s + 10) \tag{4.6}$$

From the above equation (4.6), the value for the proportional integral tuning parameters is given by

$$kc = \tau p / kp\lambda$$

$$kc = 8 / 5.3 = 1.5 \quad (4.7)$$

$$\tau i = \tau p = 8 \quad (4.8)$$

So the transfer function of proportional integral controller is now given by

$$Gc(s) = kc\ ((\tau is + 1) / (\tau is)$$

$$Gc(s) = 1.5\ ((8s + 1) / (8s)) \quad (4.9)$$

The above transfer function without delay and disturbance results in proportional integral control only.

The Simulink block diagram of ideal IMC based proportional integral derivative controller is shown in figure4.1

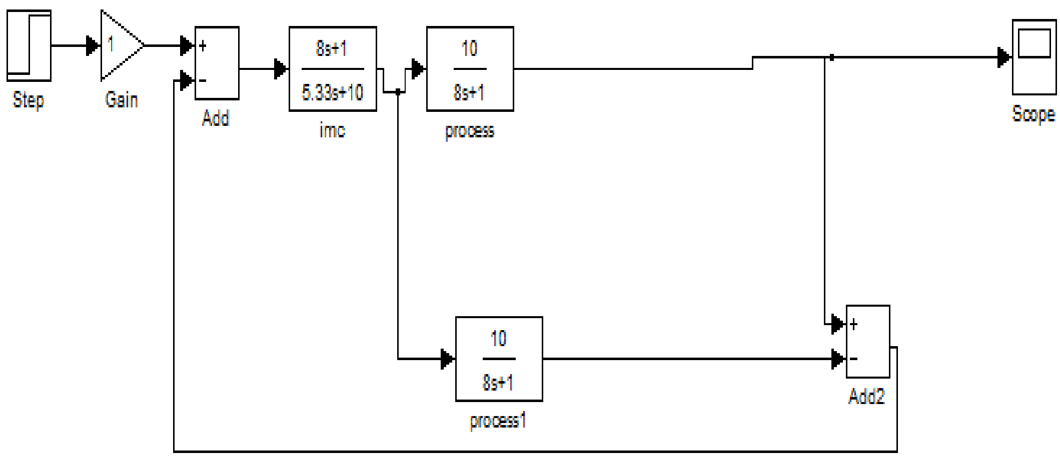

Figure 4.1: Block diagram of ideal internal model control based proportional integral derivative design

The unit step response of ideal internal model control based proportional integral derivative controller with no disturbance and time delay is shown in figure 4.2

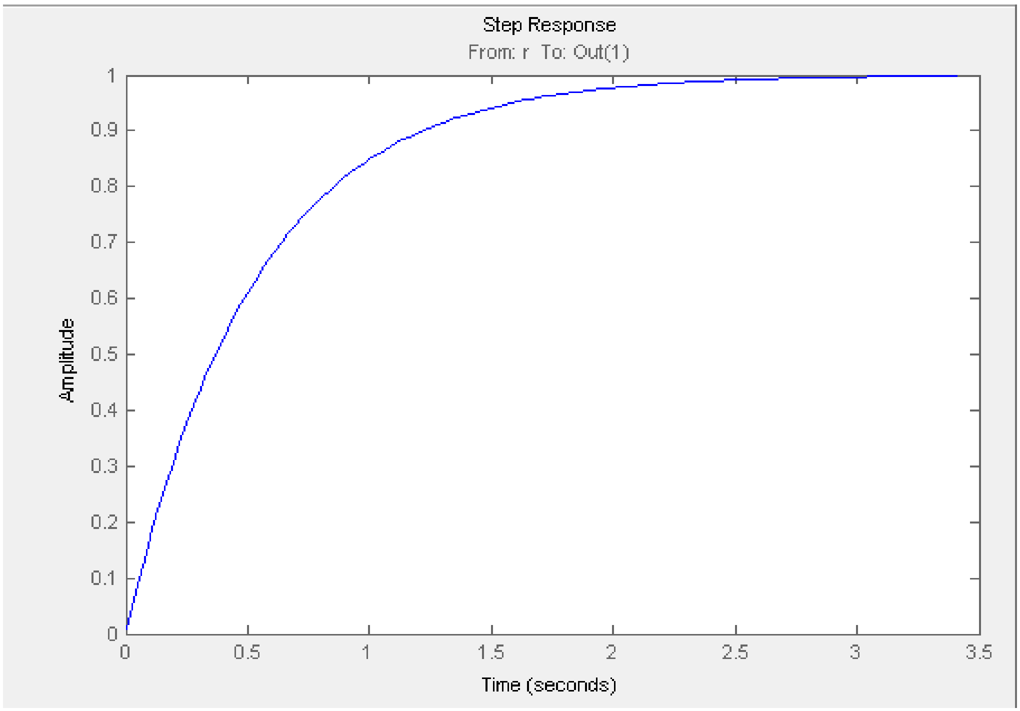

Figure 4.2: Unit step response of ideal internal model control based proportional integral derivative controller with no disturbance and time delay

4.3 Simulation of Internal Model Control Based Proportional Integral Derivative Design for a First order with Time Delay + First order disturbance

The transfer function of an internal model control based proportional integral derivative controller for a first order with time delay plus first order disturbance is is given below. The transfer function is taken from the reference papers [27]. A first order Pade's approximation is used for time delay.

$$Gp(s) = ((100 / (100s + 1)) * e^{-\theta s} \quad (4.10)$$

$$Gd(s) = (1 / (30s + 1)) \quad (4.11)$$

Gd(s) is the disturbance

θ = time delay

So $\theta = 1$

As there is time delay so first order Pade's approximation is used which is given by

$$e^{-\theta s} = (-0.5s + 1) / (0.5s + 1) \quad (4.11)$$

$$Gp(s) = (100 / (100s + 1)) * ((-0.5s + 1) / (0.5s + 1)) \quad (4.12)$$

Factor out the noninvertible elements to avoid the bad part all-pass

$$\tilde{G}p_{-} (s) = 10 / (100s + 1) (0.5s + 1) \quad (4.13)$$

$$\tilde{G}p_{+} (s) = (-0.5s + 1) \quad (4.14)$$

Now the value of $f(s) = 1 / (\lambda s + 1)^2$ to make the controller semiproper

$$Q(s) = ((100s + 1) (0.5s + 1) / 100) * 1 / (\lambda s + 1)^2 \quad (4.15)$$

Take the value of λ as 20, which is having range $\lambda > 0.2\tau p$. But practically the initial values of λ lie between one third to one fifth of time constant. Put the value of λ in equation (4.15) to get the value of IMC controller Q(s). The equation becomes

$$Q(s) = (50s^2 + 100.5s + 1) / (400s^2 + 40s + 1) \quad (4.16)$$

From the above equation (4.16), the value for the proportional integral derivative tuning parameters is given by

$$kc = (\tau p + 0.5\theta) / kp (\lambda + 0.5\theta)$$

$$kc = (100 + .5) / 100 (20 + 0.5) = 100.5 / 2050 = 0.049 \quad (4.17)$$

$$\tau i = \tau p + 0.5\theta = 100.5 \quad (4.18)$$

$$\tau D = \tau p\theta / 2 \tau p + \theta = 0.5 \quad (4.19)$$

So the transfer function of proportional integral derivative controller is now given by

$$Gc(s) = Q(s) / (1- Gp(s)\ Q(s)) \quad (4.20)$$

The Simulink block diagram of internal model control based proportional integral derivative controller for a first order with time delay plus first order disturbance is shown in figure 4.3

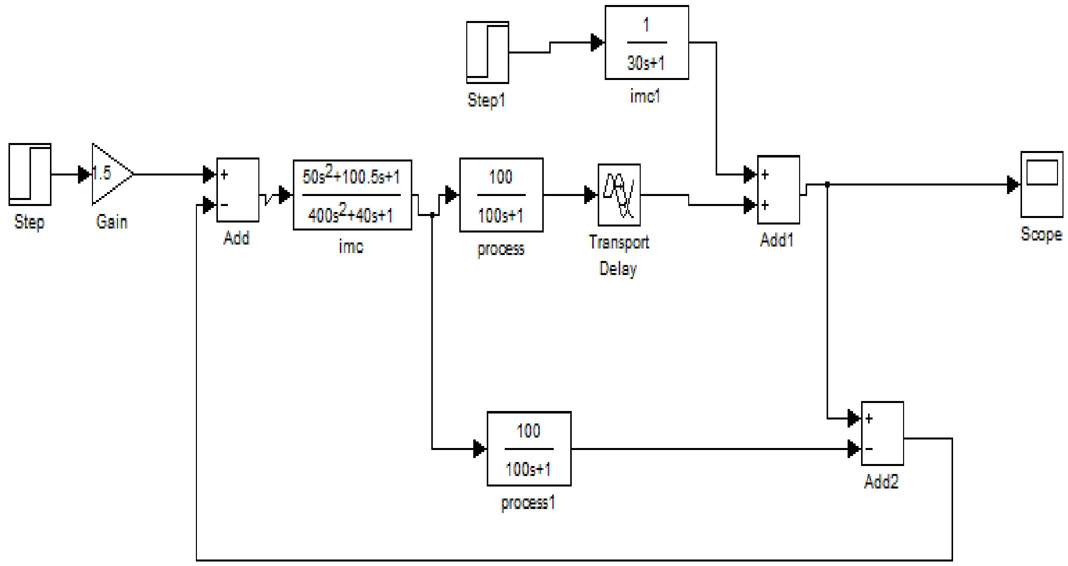

Figure 4.3: Block diagram of internal model control based proportional integral derivative controller for a first order with time delay plus first order disturbance

The unit step response of internal model control based proportional integral derivative controller for a first order with time delay plus first order disturbance is shown in figure 4.4

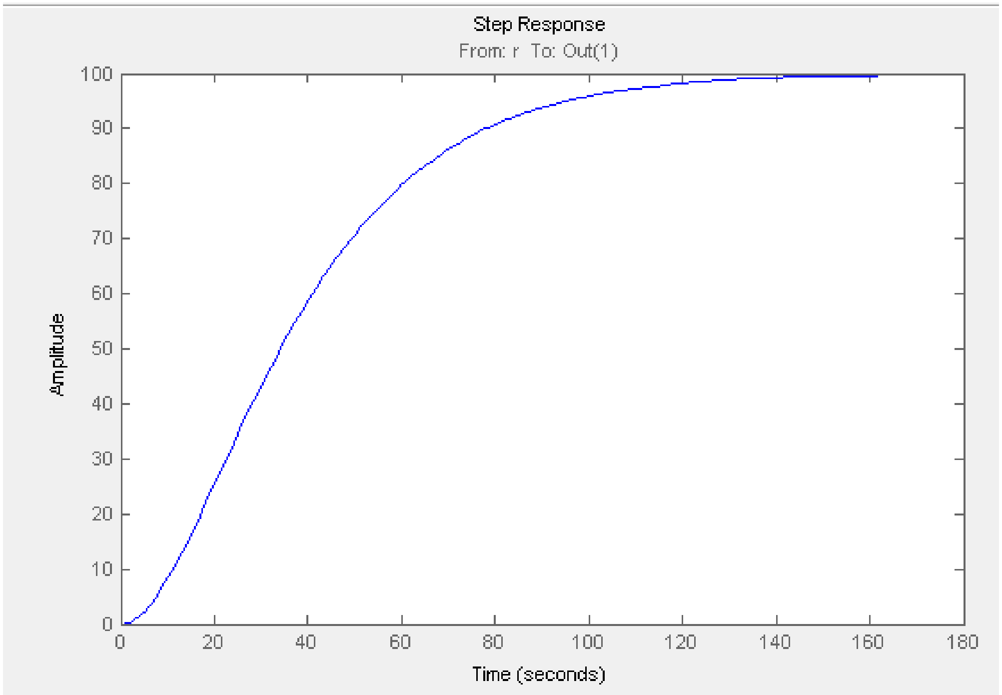

Figure 4.4: unit step response of internal model control based proportional integral derivative controller for a first order with time delay plus first order disturbance.

4.3.1 Simulation of Internal Modal Controller Based Proportional Integral Derivative Design for a First order with time delay plus second order disturbance

The transfer function of an internal model control based proportional integral derivative controller for a first order with time delay plus second order disturbance is given below. The transfer function is taken from the reference paper [27]. A first order Pade's approximation is used for time delay. In it disturbance of third order is taken which is given below and the rest of the procedure to find out and the value of the parameters of proportional integral derivative controller is the same as mentioned above

$$Gd(s) = (1 / (30s^2 + 33s + 1) \qquad (4.21)$$

The Simulink block diagram of internal model control based proportional integral derivative controller for the first order with time delay plus second order disturbance is shown in figure 4.5

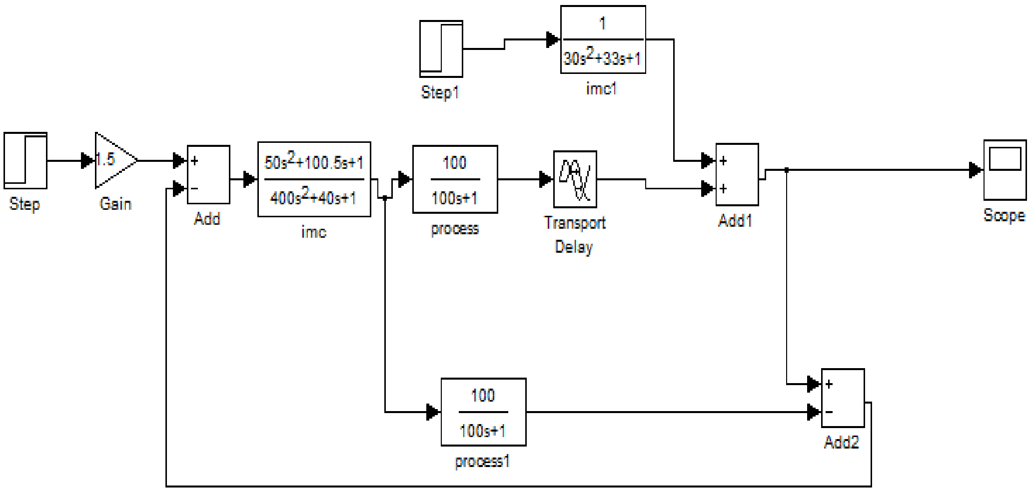

Figure 4.5: Block diagram of internal model control based proportional integral derivative controller for a first order with time delay plus second order disturbance.

The unit step response of internal model control based proportional integral derivative controller for a first order with time delay plus second order disturbance is shown in figure 4.6

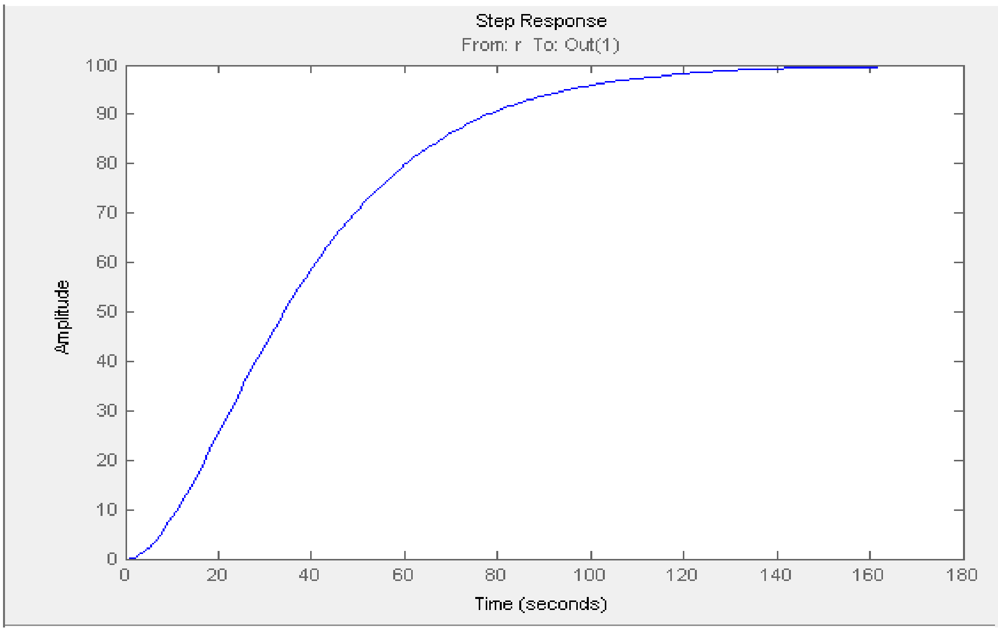

Figure 4.6: Unit step response of internal model control based proportional integral derivative controller for a first order with time delay plus second order disturbance

4.3.2 Simulation of Internal Model Control Based Proportional Integral Derivative Design for a First order with time delay plus third order disturbance

The transfer function of an internal model control based proportional integral derivative controller for a first order with time delay plus third order disturbance is given below. The transfer function is taken from the reference paper [27]. A first order Pade's approximation is used for time delay. In it disturbance of third order is taken which is given below and the rest of the procedure to find out and the value of the parameters of proportional integral derivative controller is the same as mentioned above

$$Gd(s) = / (1 / (5s^3 + 11.5s^2 + 2.5s - 1) \qquad (4.22)$$

The Simulink block diagram of internal model control based proportional integral derivative controller for the first order with time delay plus third order disturbance is shown in figure 4.7

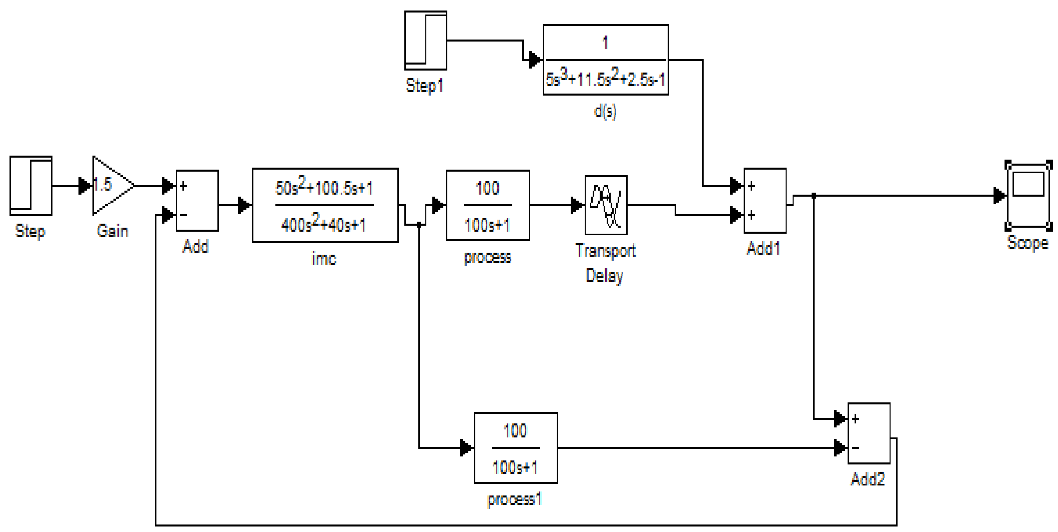

Figure 4.7: Block diagram of internal model control based proportional integral derivative controller for a first order with time delay plus third order disturbance.

The unit step response of internal model control based proportional integral derivative controller for a first order with time delay plus third order disturbance is shown in figure 4.8

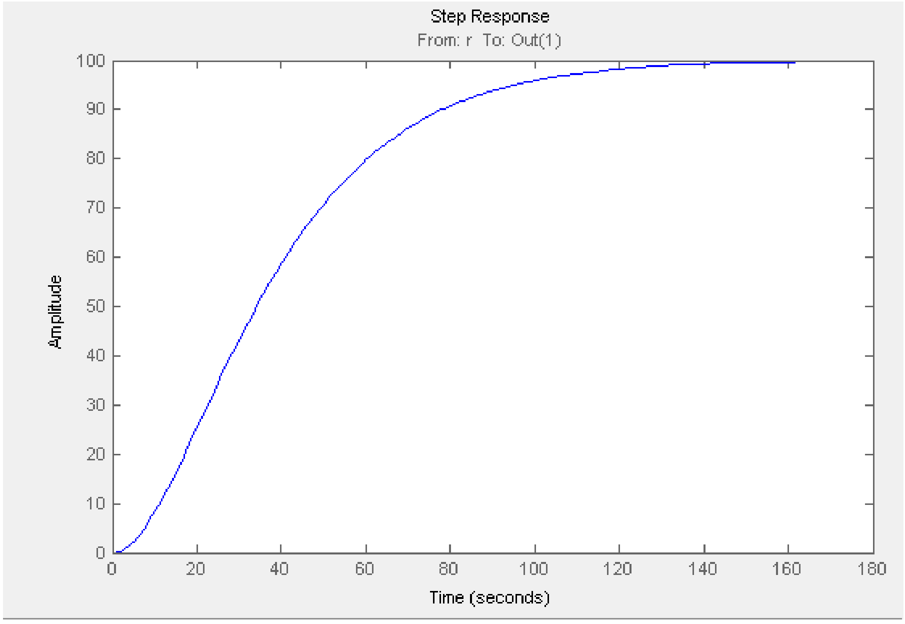

Figure 4.8: Unit step response of internal model control based proportional integral derivative controller for a first order with time delay plus third order disturbance

4.4 Simulation of Internal Model Control Based Proportional Integral Derivative Design for a Second order with time delay plus first order disturbance

The transfer function of an internal model control based proportional integral derivative controller for a second order with time plus first order disturbance is given below. The transfer function is taken from the reference papers [27]. As it is difficult to implement internal model control controller directly to higher order system due to increased complexity so it is reduced to a low order model. The method used to reduce the model is given by the half rule. According to this rule the largest neglected denominator time constant lag is distributed evenly to the effective delay and the smallest retained time constant. In it disturbance of first order is taken which is given below. A first order Pade's approximation is used for time delay.

$$Gp(s) = ((2 / (10s + 1) (5s + 1)) * e\text{-}\theta s \qquad (4.23)$$

$$Gd(s) = (1 / (30s + 1) \qquad (4.24)$$

For a first order model $\tau 2 = 0$ and the above parameters is given as

$$\tau 1 = \tau 10 + (\tau 20 / 2) \; ; \quad \theta = \theta_o + (\tau 20 / 20) + \sum_{i \geq 3} \tau i0$$

$$\tau 1 = 12.5; \; k = 2 \; ; \tau 2 = 0 \; ; \theta = 3.5 \qquad (4.25)$$

By using half rule reduced model is given as

$$Gp(s) = (2 / 12.5s + 1) * e\text{-}3.5\theta s \qquad (4.26)$$

As there is time delay so first order Pade's approximation is used which is given by

$$e\text{-}3.5\theta s \quad = (-1.75s + 1) / (1.75s + 1) \qquad (4.27)$$

$$Gp(s) = (2 / (12.5s + 1)) * ((-1.75s + 1) / (1.75s + 1)) \qquad (4.28)$$

Factor out the noninvertible elements to avoid the bad part all-pass

$$\tilde{G}p\text{-} (s) = 2 / (12.5s + 1) (1.75s + 1) \qquad (4.29)$$

Now the value of $f(s) = 1 / (\lambda s + 1)^2$ to make the controller semiproper

$$Q(s) = ((12.75s + 1) (1.75s + 1) / 2) * 1 / (\lambda s + 1)^2 \qquad (4.30)$$

Take the value of λ as 3, which is having range $\lambda > 0.2\tau p$. But practically the initial values of λ lie between one third to one fifth of time constant. Put the value of λ in equation (4.30) to get the value of internal model control controller Q(s). The equation becomes

$$Q(s) = (21.875s^2 + 14.25s + 1) / (18s^2 + 12s + 2) \qquad (4.31)$$

The value for the proportional integral derivative tuning parameters is given by

$$\tau c = \theta = 3.5 \quad (4.32)$$

$$k1 = k / \tau 10 = 0.2 \quad (4.33)$$

$$kc = (1 / k1) * (1 / \tau c + \theta) = 0.312 \quad (4.34)$$

$$\tau i = 8\theta = 8*3.5 = 28 \quad (4.35)$$

$$\tau D = \tau 2 = 5 \quad (4.36)$$

By getting the above values PID transfer function can be evaluated.

The Simulink block diagram of internal model control based proportional integral derivative controller for the second order with time delay plus first order disturbance is shown in figure 4.9

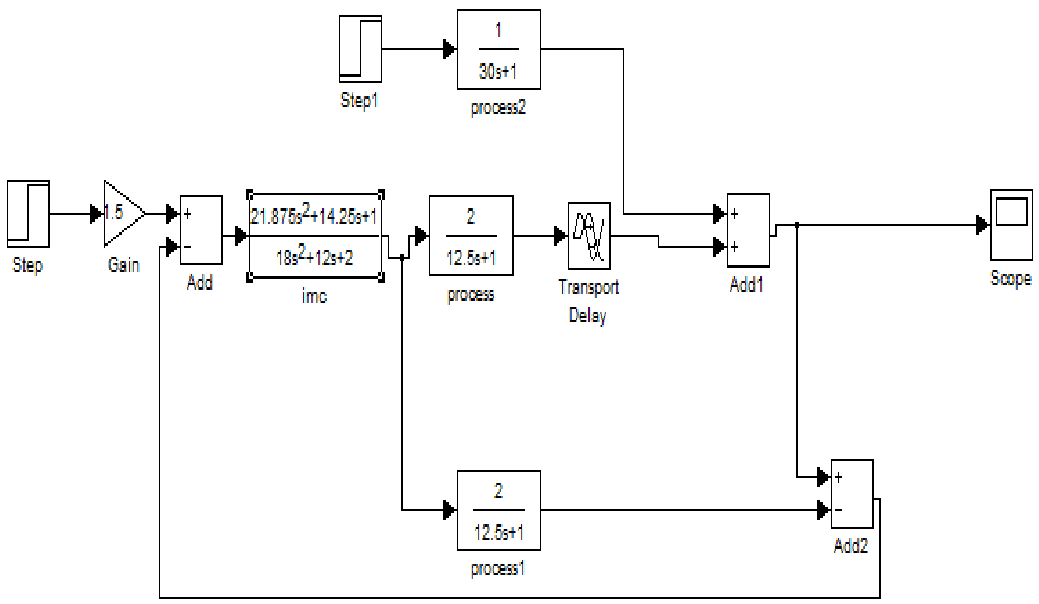

Figure 4.9: Block diagram of internal model control based proportional integral derivative controller for a second order with time delay plus first order disturbance.

The unit step response of internal model control based proportional integral derivative controller for a second order with time delay plus first order disturbance is shown in figure 4.10

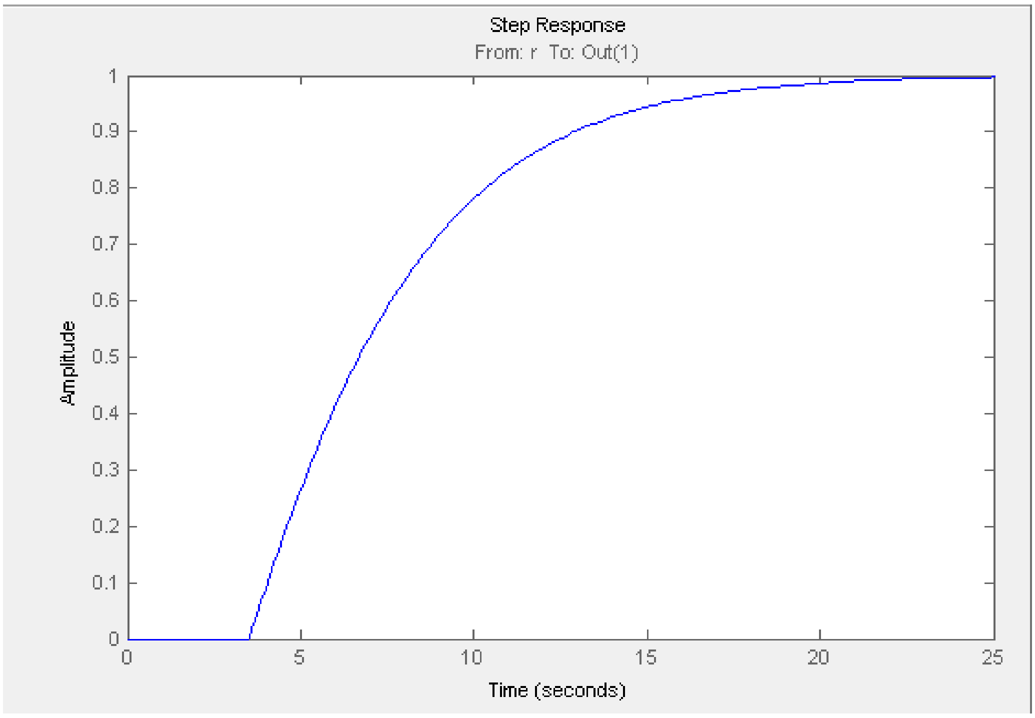

Figure 4.10: Unit step response of internal model control based proportional integral derivative controller for a second order with time delay plus first order disturbance

4.4.1 Simulation of Internal Model Control Based Proportional Integral Derivative Design for a Second order with time Delay plus second order disturbance

The transfer function of an internal model control based proportional integral derivative controller for a second order with time delay plus second order disturbance is given below. The transfer function is taken from the reference paper [27]. A first order Pade's approximation is used for time delay. In it disturbance of first order is taken which is given below and the rest of the procedure to find out and the value of the parameters of proportional integral derivative controller is the same as mentioned above

$$Gd(s) = (1 / (30s^2 + 33s + 1) \qquad (4.37)$$

The Simulink block diagram of internal model control based proportional integral derivative controller for the second order with time delay plus second order disturbance is shown in figure 4.11

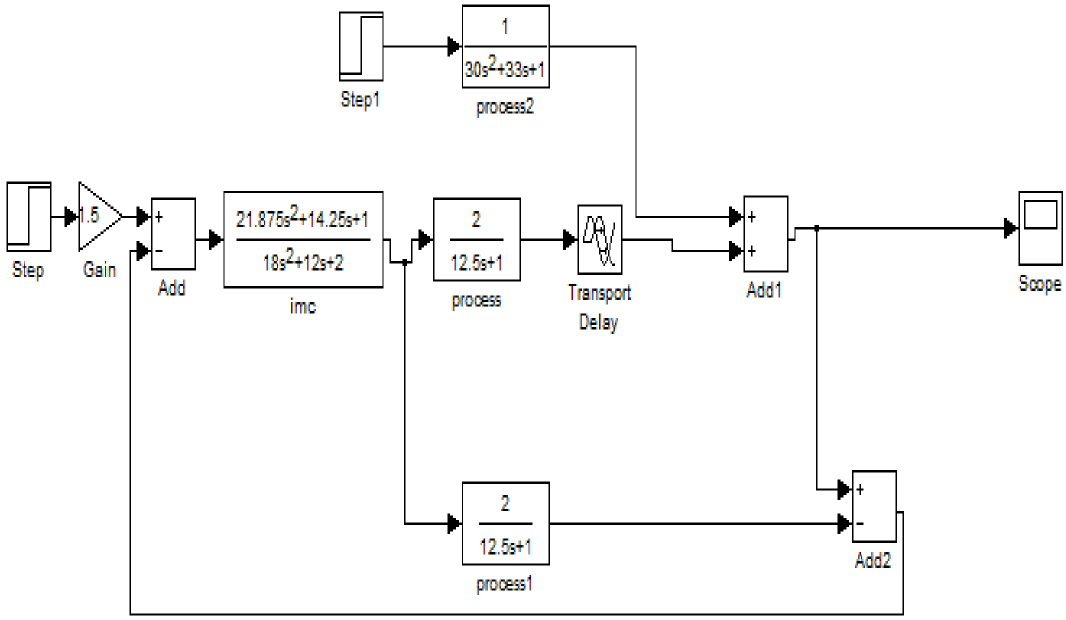

Figure 4.11: Block diagram of internal model control based proportional integral derivative controller for the second order with time delay plus second order disturbance

The unit step response of IMC based proportional integral derivative controller for a second order with time delay plus second order disturbance is shown in figure 4.12

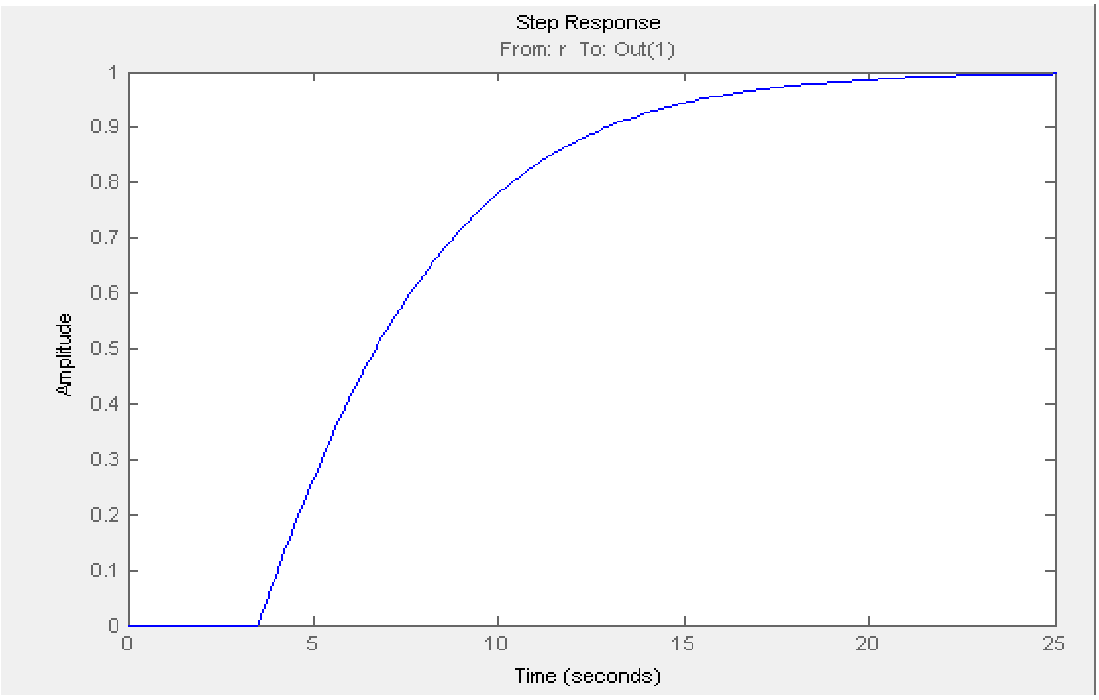

Figure 4.12: Unit step response of internal model control based proportional integral derivative controller for a second order with time delay plus second order disturbance

4.4.2 Simulation of Internal Model Control Based Proportional Integral Derivative Design for a Second order with time Delay plus third order disturbance

The transfer function of an internal model control based proportional integral derivative controller for a second order with time delay plus third order disturbance is given below. The transfer function is taken from the reference paper [27]. A first order Pade's approximation is used for time delay. In it disturbance of first order is taken which is given below and the rest of the procedure to find out and the value of the parameters of proportional integral derivative controller is the same as mentioned above

$$Gd(s) = (1 / (5s^3 + 11.5s^2 + 2.5s - 1) \qquad (4.38)$$

The Simulink block diagram of internal model control based proportional integral derivative controller for the second order with time delay plus third order disturbance is shown in figure 4.13

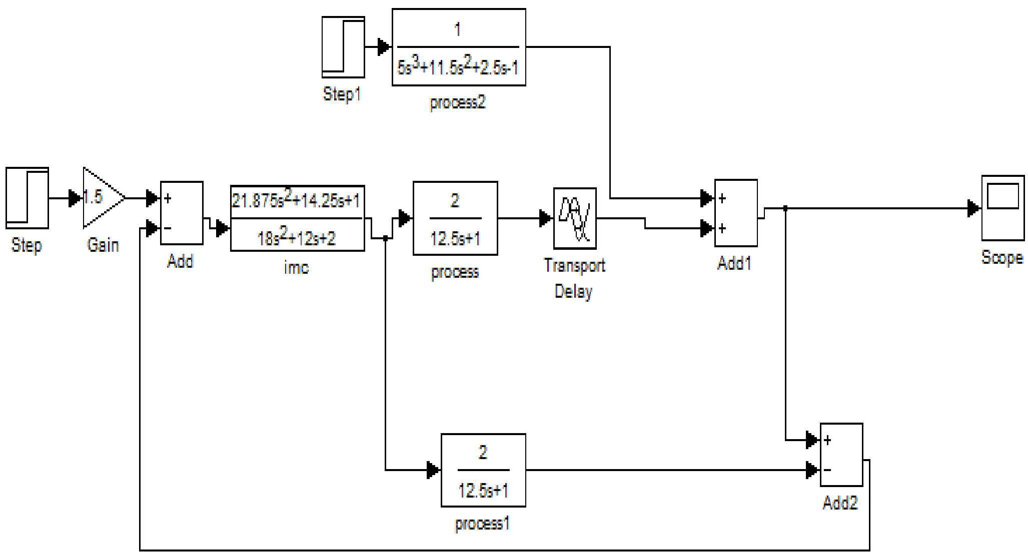

Figure 4.13: Simulink block diagram of internal model control based proportional integral derivative controller for the second order with time delay plus third order disturbance

The Unit step response of internal model control based proportional integral derivative controller for the second order with time delay plus third order disturbance is shown in figure 4.14

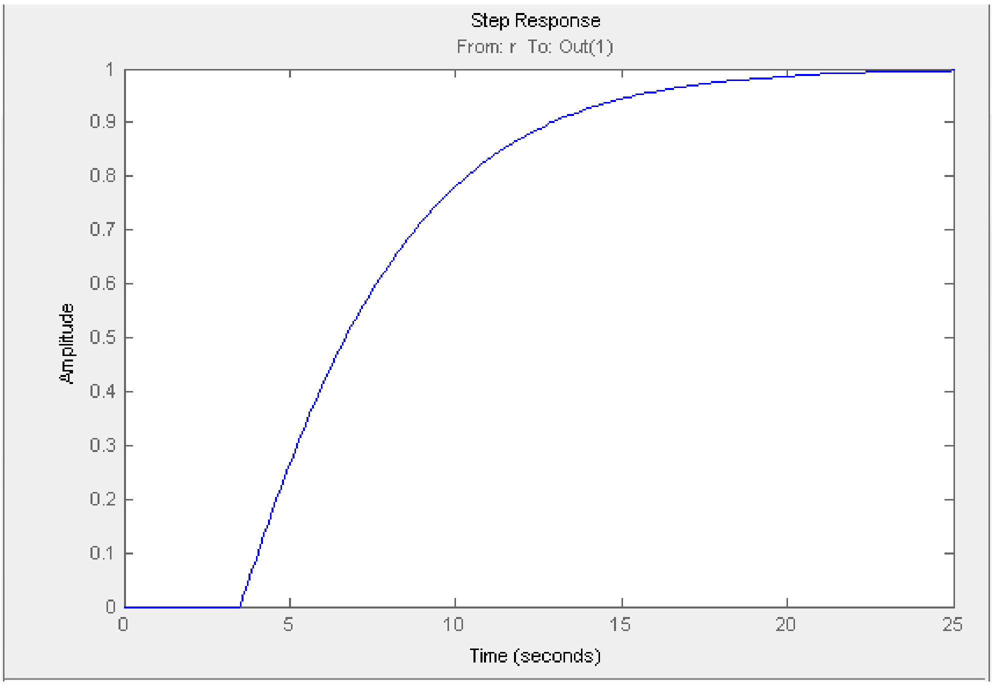

Figure 4.14: Unit step response of internal model control based proportional integral derivative controller for the second order with time delay plus third order disturbance

4.5 Simulation of Internal Model Control Based Proportional Integral Derivative Design for a third order with time Delay plus first order disturbance

The transfer function of an internal model control based proportional integral derivative controller for a third order with time delay plus first order disturbance is given below. The transfer function is taken from the reference papers [36]. As it is difficult to implement internal model controller directly to higher order system due to increased complexity so it is reduced to a low order model. The method used to reduce the model is given by the half rule. According to this rule the largest neglected denominator time constant lag is distributed evenly to the effective delay and the smallest retained time constant. In it disturbance of first order is taken which is given below. A first order Pade's approximation is used for time delay.

$$Gp(s) = ((2 / (2s + 1) (s + 1)^2) * e{-}\theta s \qquad (4.39)$$

$$Gd(s) = (1 / (30s + 1) \qquad (4.40)$$

For a first order model $\tau 2 = 0$ and the above parameters is given as

$$\tau 1 = \tau 10 + (\tau 20 / 2) ; \quad \theta = \theta_o + (\tau 20 / 20) + \sum_{i \geq 3} \tau i0$$

$$\tau 1 = 2.5 ; \; k = 2 ; \tau 2 = 0 ; \theta = 1.5 \qquad (4.41)$$

By using half rule reduced model is given as

$$Gp(s) = (2 / 2.5s +1) * e{-}1.5\theta s \qquad (4.42)$$

As there is time delay so first order Pade's approximation is used which is given by

$$e{-}3.5\theta s \quad = (-0.75s + 1) / (0.75s + 1) \qquad (4.43)$$

$$Gp(s) = (2 / (2.5s + 1)) * ((-0.75s + 1) / (0.75s + 1)) \qquad (4.44)$$

Factor out the noninvertible elements to avoid the bad part all-pass

$$\tilde{G}p{-} (s) = 2 / (2.5s + 1) (0.75s + 1) \qquad (4.45)$$

Now the value of $f(s) = 1 / (\lambda s + 1)^2$ to make the controller semiproper

$$Q(s) = ((2.75s + 1) (0.75s + 1) / 2) * 1 / (\lambda s + 1)^2 \qquad (4.46)$$

Take the value of λ as 1, which is having range $\lambda > 0.2\tau p$. But practically the initial values of λ lie between one third to one fifth of time constant. Put the value of λ in equation (4.30) to get the value of IMC controller Q(s). The equation becomes

$$Q(s) = (1.875s^2 + 3.25s + 1) / (2s^2 + 4s + 2) \quad (4.47)$$

The value for the proportional integral derivative tuning parameters is given by

$$\tau c = \theta = 1.5 \quad (4.48)$$

$$k1 = k / \tau 10 = 1 \quad (4.49)$$

$$kc = (1 / k1) * (1 / \tau c + \theta) = 0.33 \quad (4.50)$$

$$\tau i = 8\theta = 8*1.5 = 12 \quad (4.51)$$

$$\tau D = \tau 2 = 1$$

By getting the above values proportional integral derivative transfer function can be evaluated.

The Simulink block diagram of internal model control based proportional integral derivative controller for the third order with time delay plus first order disturbance is shown in figure 4.15

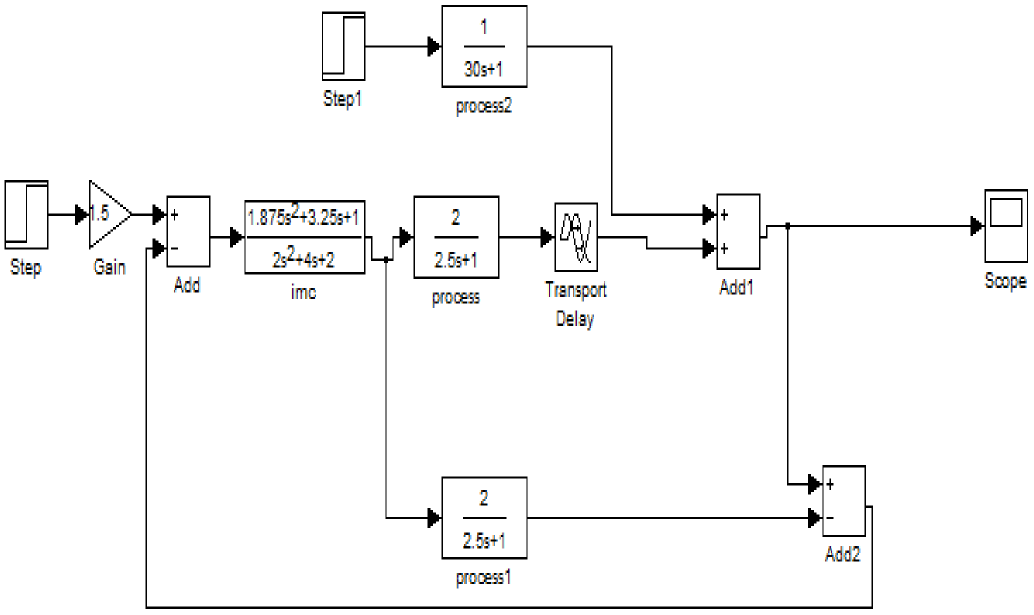

Figure 4.15: Simulink block diagram of internal model control based proportional integral derivative controller for the third order with time delay plus first order disturbance

The unit step response of internal model control based proportional integral derivative controller for the third order with time delay plus first order disturbance is shown in figure 4.16

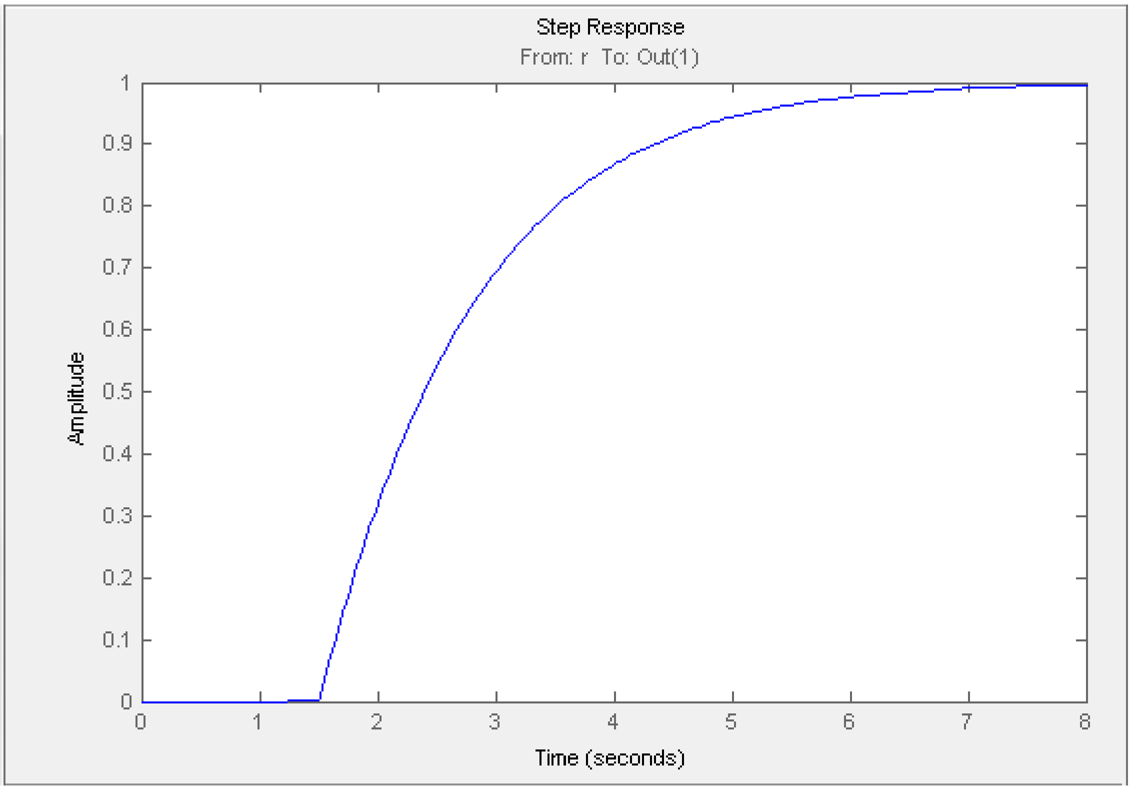

Figure 4.16: Unit step response of internal model control based proportional integral derivative controller for the third order with time delay plus first order disturbance.

4.5.1 Simulation of Internal Model Control Based Proportional Integral Derivative Design for a third order with time Delay plus second order disturbance

The transfer function of an internal model control based proportional integral derivative controller for a third order with time delay plus second order disturbance is given below. The transfer function is taken from the reference paper [36]. A first order Pade's approximation is used for time delay. In it disturbance of first order is taken which is given below and the rest of the procedure to find out and the value of the parameters of Proportional Integral Derivative controller is the same as mentioned above

$$Gd(s) = \quad (1 / (30s^2 + 33s + 1) \qquad (4.52)$$

The Simulink block diagram of internal model control based proportional integral derivative controller for the third order with time delay plus second order disturbance is shown in figure 4.17

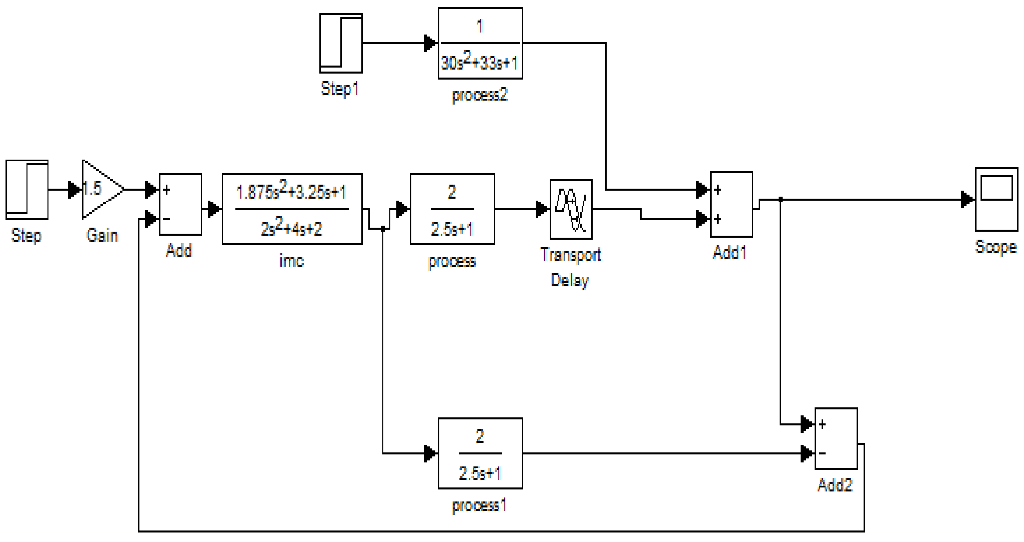

Figure 4.17: Simulink block diagram of internal model control based proportional integral derivative controller for the third order with time delay plus second order disturbance

The unit step response of internal model control based proportional integral derivative controller for the third order with time delay plus second order disturbance is shown in figure 4.18

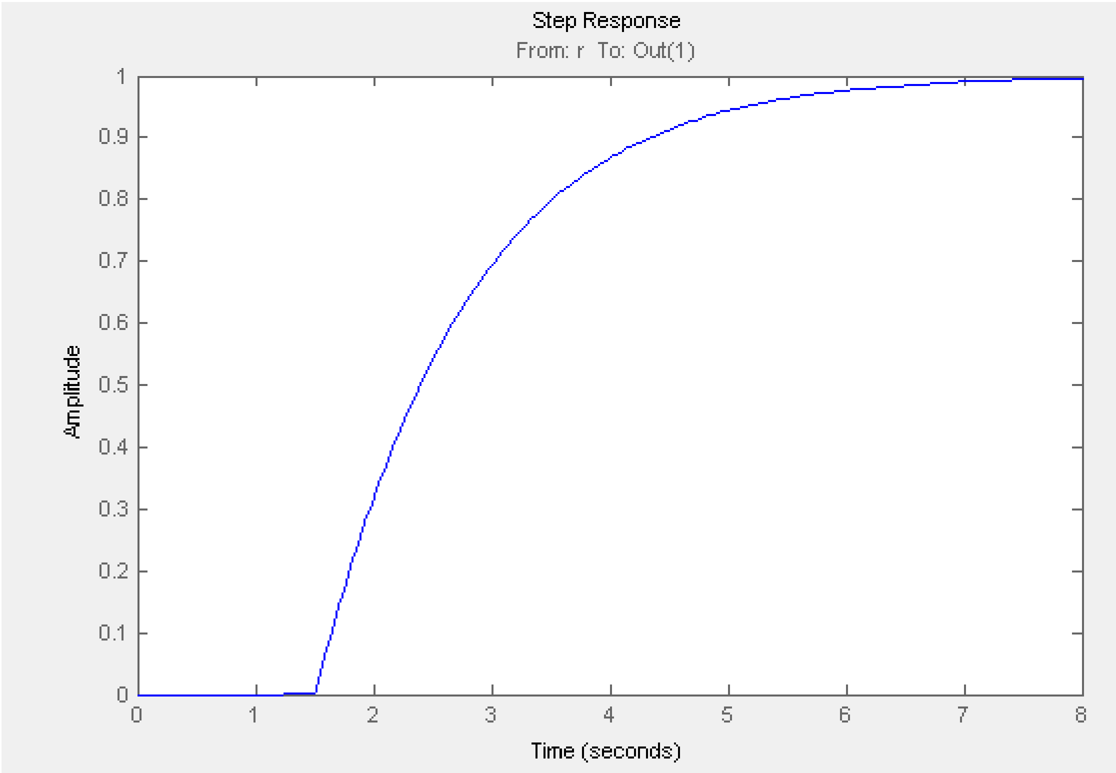

Figure 4.18: Unit step response of internal model control based proportional integral derivative controller for the third order with time delay plus second order disturbance

4.5.2 Simulation of Internal Model Control Based Proportional Integral Derivative Design for a third order with time Delay plus third order disturbance

The transfer function of an internal model control based proportional integral derivative controller for a third order with time delay plus third order disturbance is given below. The transfer function is taken from the reference paper [36]. A first order Pade's approximation is used for time delay. In it disturbance of first order is taken which is given below and the rest of the procedure to find out and the value of the parameters of proportional integral derivative controller is the same as mentioned above

$$Gd(s) = (1 / (5s^3 + 11.5s^2 + 2.5s - 1) \quad (4.53)$$

The Simulink block diagram of internal model control based proportional integral derivative controller for the third order with time delay plus third order disturbance is shown in figure 4.19

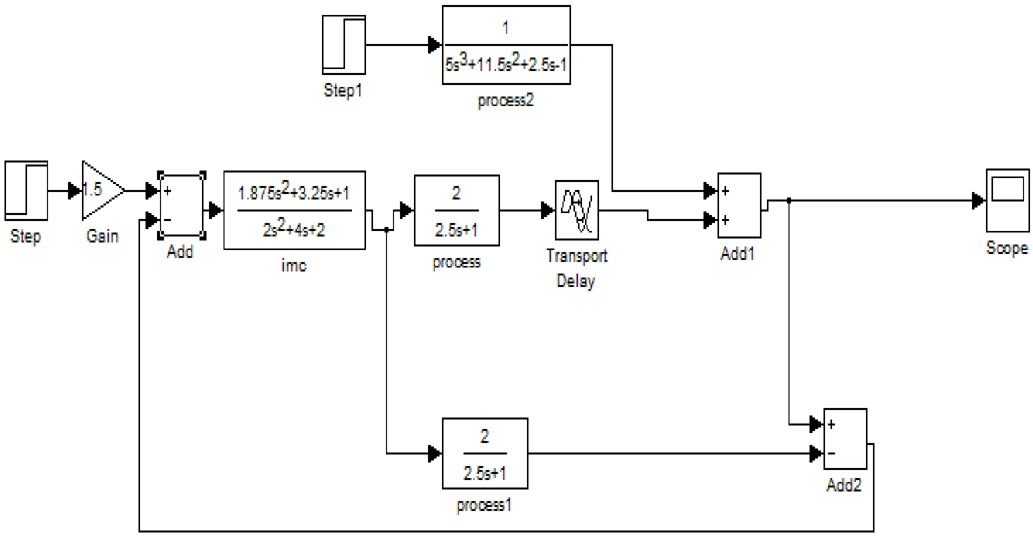

Figure 4.19: Simulink block diagram of internal model control based proportional integral derivative controller for the third order with time delay plus third order disturbance

The unit step response of internal model control based proportional integral derivative controller for the third order with time delay plus third order disturbance is shown in figure 4.20

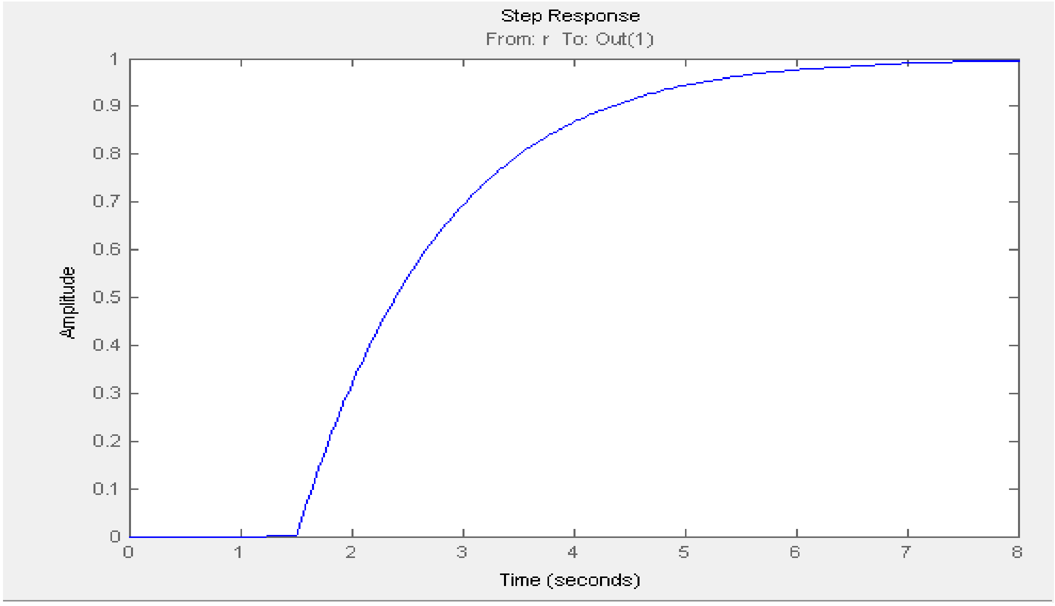

Figure 4.20: Unit step response of internal model control based proportional integral derivative controller for the third order with time delay plus third order disturbance

Various tuning parameters of internal model control based proportional integral derivative design based on different orders of transfer functions obtained from above are shown in table 4.1.s

Orders of Transfer functions	**kc**	**τi**	**τd**	**τc**
Ideal IMC based PID	1.5	8	-	-
First order IMC based PID	0.049	100.5	0.5	-
Second order IMC based PID	0.312	28	5	3.5
Third IMC based PID	0.33	12	1	1.5

Table 4.1: Various tuning parameters of internal model control based proportional integral derivative design based on different orders of transfer functions

CHAPTER 5
CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

The internal model controller provides a transparent frame work for control system design and tuning. The internal model control based proportional integral derivative controller design is simple and robust to handle the model uncertainties and disturbances and less sensitive to noise than proportional integral derivative controller for an actual process in industries. The internal model control based proportional integral derivative controllers design results in only one tuning parameter which is closed loop time constant λ internal model control filter factor. The internal model control based proportional integral derivative tuning parameters are then a function of closed loop time constant. The selection of the closed-loop time constant is directly related to the robustness sensitivity to model error of the closed-loop system.

The internal model control based proportional integral derivative design procedure can be implemented in industrial processes using existing proportional integral derivative control equipment. It also provides a good solution to the process with significant time delays which is actually the case with working in real time environment. The internal model control based proportional integral derivative controller design is used for open loop unstable processes because the internal model control suffers from internal stability.

There is a time delay in the system which affects the output of a system. So Pade's approximation for the time delays in internal model control based proportional integral derivative controller design is used along with half rule to handle the complex models by approximating the remaining high order dynamics by an effective delay. By comparing the figures of unit step responses it is proved that the internal model control based proportional integral derivative controller will not give the same results as the internal model control strategy because of approximation used for Delay time. And also various tuning parameters have been found based on the different orders of transfer functions. The standard internal model control filter from $f(s) = 1 / (\lambda s + 1)$

shows good set point tracking. Thus internal model control based proportional integral derivative controller is able to compensate for disturbances and model uncertainty while open loop control is not. Internal model controller is also detuned to assure stability even if there is model uncertainty.

5.2 Future Scope

The internal model control based proportional integral derivative controller design is conventional controller. So due to speed in their execution, accuracy of control, ease of configuration, low energy consumption, probability etc, artificial intelligence based controllers such as Fuzzy logic based controllers and Artificial Neural Network based controller can be used.

REFERENCES

1. J. G. Ziegler, N. B. Nichols, Optimum settings for automatic controllers, Transactions of the ASME, pp. 759-768, 1942.

2. G. H. Cohen, G. A. Coon, Theoretical Consideration of Retarded Control, Transactions of the ASME, Vol. 65, pp. 827-834, 1953.

3. C. E. Garcia, M. Morari, Internal Model Control. 1. A Unifying Review and Some New Results, Industrial & Engineering Chemistry Process Design and Development,Vol. 21, pp.308-323, 1982.

4. Costas Kravaris, Raymond A. Wright, Deadtime Compensation for Nonlinear Processes, AIChE Journal,Vol. no 35, No.9, pp. 1535-1542, 1989.

5. John Doyle, Bruce Francis, Allen Tannenbaum, Feedback Control Theory, @ Macmillan Publishing Co, pp. 31-34, 1990.

6. K. J. Aström, T. Hagglund, PID Controllers: Theory, Design, and Tuning, 2nd ed, Instrument Society of America, 1995.

7. Gao Jinchang , Zhou Chunhui, Gong Xiaofeng, Extension of IMC tuning to improve controller performance, Systems, Man, and Cybernetics, IEEE International Conference, Vol. no. 3, pp. 1770-1775, 1996.

8. Ian G. Horn, Jeffery R. Arulandu, Christopher J. Gombas, Jeremy G. VanAntwerp, and Richard D. Braatz, Improved filter design in internal model control, Industrial Engineering Chemical Resources, Vol.no 36, pp.3437-3441, 1996.

9. Lee, Y., Park, S., Lee, M., Brosilow, C., PID controller tuning for desired closed-loop responses for SI/SO systems. AIChE J., Vol. no 44, pp.106-115, 1998.

10. Syder J, T Heeg, and A O'Dwyer, Dead-time Compensators: Performance and Robustness Issues, European Journal of Control, pp. 166-171, 2000.

11. Tim Wescott, PID without a PhD, EE Times-India, pp.10, 2000.

12. Sigurd Skogestad, Probably the best simple PID tuning rules in the world, Journal of Process Control, pp. 1-27, 2001.

13. G.K.I.Mann, B.-G.Hu and R.G.Gosine, Time-domain based design and analysis of new PID tuning rules, IEE Proceedings.-Control Theory Application, Vol. 148, no.3, pp. 251-261, 2001.

14. Tony Hong, Peter C Hughes, Effect of Time Delay on the Stability of Flexible Structures with Rate Feedback Control, journal of vibration and control, Vol. no.7, pp. 33-49, 2001.

15. Chen, D., Seborg, D. E., PI/PID controller design based on direct synthesis and disturbance rejection, Industrial Engineering Chemical Resources, Vol. 41 no 19, pp. 4807-4822, 2002.

16. Mustafa A.A, Hasan M, Sanjay Jha, Design and performance evaluation of a rate feedback control architecture for TCP/IP networks, proceedings of the performance, computing and communications conference, 2[1st] IEE internationals, pp. 251-258, 2002.

17. Sigurd Skogestad, Simple Analytic Rules for Model Reduction and PID Cotroller tuning, Journal of Process Control, Vol. no 13, pp. 291-309, 2003.

18. A. O’Dwyer, Handbook of PI and PID Controller Tuning Rules, Imperial College Press, London,pp. 37, 2003.

19. B wayne Bequette, Process Control: Modelling, Design, and Simulation, Prentice Hall, pp. (198-206),(294-297),(262-264) 2003

20. Qing-Guo Wang , Han-Qin Zhou, Yu Zhangt and Yong Zhang, A Comparative Study on Control of Unstable Processes with Time Delay, 5th Asian Control Conference, pp. 1996-2004, 2004

21. K. J. Aström, T. Hagglund, Revisiting the Ziegler-Nichols step response method for PID control, Journal of Process Control, Vol. 14, pp. 635-650, 2004.

22. Kiam Heong Ang, Gregory Chong, Student Member, IEEE, and Yun Li, Member, IEEE, PID Control System Analysis, Design, and Technology, IEEE Transactions on control system technology, Vol. 13, NO. 4, pp. 559-576, 2005.

23. Micheal A,Johnson,Mohammad H, Morradi, PID control:New Identification and design methods,@ Springer-verlag London limited, pp. 7-9,22-24, 30-32, 2005.

24. Ang, K.H., Chong, G.C.Y., and Li, Y., PID control system analysis, design, and technology, IEEE Trans Control Systems Tech, Vol. no. 13, pp.559-576. 2005.

25. K. J. Astrom, T. Hagglund, Advanced PID Control, Instrument Society of America, 2005.

26. Wen Tan, Jizhen Liu, Tongwen Chen, Horacio J. Marquez, Comparison of some well-known PID tuning formulas, Published by Elsevier Ltd. , Computers and Chemical Engineering 30, pp. 1416–1423, 2006.

27. M. Shamsuzzoha and Moonyong Lee, IMC-PID Controller Design for Improved Disturbance Rejection of Time Delayed Processes, Industrial Engineering Chemical Resources, Vol. no. 46, pp. 2077-2091, 2007.

28. Truong Nguyen Luan Vu, Jietae Lee, and Moonyong Lee, Design of Multi-loop PID Controllers Based on the Generalized IMC-PID Method with Mp Criterion, International Journal of Control, Automation, and Systems, Vol. no. 5, no. 2, pp. 212-217, 2007.

29. Michel Fliess and Cedric Join, “ Intelligent PID controllers”, 16th Mediterranean Conference on Control and Automation Congress Centre, France, pp. 326-331, 2008.

30. R. Farkh, K. Laabidi and M. Ksouri, PI Control for Second Order Delay System with Tuning Parameter Optimization, International Journal of Electrical and Electronics Engineering, pp. 1-7, 2009.

31. Tao Liu, Furong Gao ,Youqing Wang, IMC-based iterative learning control for batch processes with uncertain time delay, Journal of Process Control, Vol. no 20, Issue 2, pp. 173–180, 2010.

32. Araki M., Control Systems, Robotics, and Automation - PID Control, Kyoto University, Japan, Vol. II, 2010.

33. Susmita Das, Ayan Chakraborty, Jayanta Kumar Ray, Soumyendu Bhattacharjee, Dr. Biswarup Neogi, Study on Different Tuning Approach with Incorporation of Simulation Aspect for Z-N (Ziegler-Nichols) Rules, International Journal of Scientific and Research Publications, Vol. no 2, Issue 8, pp. 1-5, 2012.

34. V. Kongratana, V. Tipsuwanporn, A. Numsomran and A. Detchrat, IMC-Based PID Controllers Design for Torsional Vibration System, 12th International Conference on Control, Automation and Systems Oct. 17-21, Korea, pp. 892-895, 2012.

35. QIN Gang, SONG Le, HU Ling, A Practical Application of IMC-PID Controller in Unmanned Vehicle, Telkomnika, Vol. 11, No. 6, pp. 3228-3235, e-ISSN: 2087-278X, 2013.

36. Linkan Priyadarshini, J.S Lather, Design of IMC-PID Controller for a Higher order system and its Comparison with Conventional PID Controller, International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering,Vol. 1, Issue 3, pp.108-112, 2013

Thanks to search engine Google, Self explanatory Wikipedia, Various advanced journals websites, Our Thapar university Nav Nalanda Library, Our Departmental Library, Engineering Books of Various Indian And Foreign authors, Science tool for making scientific logics available.