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# Modeling and Designing of Controllers for pH Process

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## ABSTRACT

Studies on pH control in process engineering have shown a dramatic increase in the last decades. pH control systems were developed and used successfully on various applications of pH process plants in many industries especially in chemical processes, biotechnological industries, wastewater treatment and pharmaceuticals. The pH process is considered as a benchmark problem. Thus the research is ongoing on identification and control in pH process. In this paper, the mathematical model has been developed for a chemical process (pH process) and the conventional controllers such as PI and PID, Tyreus-Luyben has been designed and implemented. A control strategy based on tuning of a PID controller with Internal model controller (IMC), Direct synthesis method has been designed and implemented in the pH process. The experimental and simulation results obtained by various control algorithms are discussed.

**Keywords**: pH Process, PI & PID controller, Tyreus-Luyben, IMC and Direct synthesis.

## 1. INTRODUCTION

An extensive research in the identification of pH process has been done by many relative experts for many years. The ionic product of $H_2O$ is given by HCl+NaOH=NaCl+$H_2O$and its pH neutral (ie.7). Since in pure water the concentration of H+ ion is equal to the concentration of hydroxide ion $OH^-$ any addition of $H^+$ ion will make it acidic and $OH^-$ ion will make it base. The addition of $H^+$ may be due to the addition of acids and acidic impurities to the water stream by the industries manufacturing acids or industries using acids in one or more of their manufacturing stages. Similarly the $OH^-$ may be from the industries manufacturing alkalis such as KOH, NaOH, etc. and also from those industries using alkalis in one or more of their manufacturing stages. So in order to make the pH within specific limit the acidic water the alkaline should be added and vice versa.

The primary objective is to develop a dynamic nonlinear pH process model, based on physical and chemical principles that can represent the specific pH process. The accuracy of this model should be sufficient to allow the development of conventional and advanced control systems through simulation for subsequent implementation and testing on the plant itself. The pH neutralization process is modelled based on the reaction between strong basic solution (NaOH) and strong acidic solution (HCL) in Continuous Stirred Tank Reactor (CSTR).

A PID controller is most commonly used in industrial control systems. PID controller has three principle control effects. The proportional (P) action gives a change in the input (manipulated variable) directly proportional to the error signal. The integral (I) action gives a change in the input proportional to the integral of error, and its main purpose is to eliminate offset. Whereas the derivative (D) action is used to speed up the response or to stabilize the system and it gives a change in the input proportional to the derivative of the error signal. The overall controller output is the sum of the contributions from these three terms The general form of the PID controller is given below in equation (1).

$$u(t) = K_P e(t) + \frac{1}{T_I}\int_0^t e(t)dt + T_D \frac{de(t)}{d(t)} \quad (1)$$

Where u(t) and e(t) denote the control and the error signals, respectively, and proportional gain ($K_P$) integral time ($T_I$) and derivative time ($T_D$) are the parameters to be tuned [1].

The Ziegler–Nichols tuning method is a heuristic method of tuning a PID controller. It was developed by John G. Ziegler and Nathaniel B. Nichols. It is performed by setting the I (integral) and D (derivative) gains to zero [4]. The Proportional gain $K_P$ is then increased (from zero) until it reaches the ultimate gain $K_u$ at which the output of the control loop oscillates with constant amplitude. $K_U$ and the oscillation period $T_U$ are used to set the P, I, and D gains depending on the type of controller's used [7].

The Tyreus-Luyben method is also called as online tuning method. They had developed tuning method in closed-loop mode. This closed-loop tuning method overcomes the shortcoming of the well-known Ziegler-Nichols continuous cycling method and gives consistently better performance and robustness for broad class of processes.[7]. This is a more conservative approach than Ziegler-Nicholas method and so it gives better performance with small values for dead time. But when the value of dead time is large it gives a sluggish performance [6].

This method depends upon internal model principle, which states that control can be attained only if the control system encapsulates either implicitly or explicitly. The IMC approach has two important advantages are as it explicitly considers model uncertainty and it allows the designer to trade-off control system performance against control system robustness to process changes and modelling errors [8].

In the direct synthesis (DS) approach, however, the controller design is based on a desired closed-loop transfer function.DS design methods are usually based on specification of the desired closed-loop transfer function for set-point changes. Consequently, the resulting DS-d controllers tend to perform well for set-point changes & the disturbance response might be satisfactory [9].

Mostly every system will have many objectives to be achieved. For designing a controller by satisfying all the requirements, algorithms are needed so as to tackle the problems that may arise. The conventional tuning methods which works based on fixed parameters will result in lesser performance when system necessitates controller. The next section briefly explains about the mathematical modelling and different tuning techniques such as Ziegler-Nichols (ZN), Tyreus-Luyben (T-L), Direct Synthesis method and Internal Model Controller for designing the PID controllers. From the above specified tuning methods, the proportional band, integral time and derivative time can be calculated. By using those values one can determine the Proportional constant ($K_C$), Integral constant ($K_I$) and Derivative constant ($K_D$). It also includes the PID values [$K_C$,$K_I$,$K_D$] of the four tuning method's and the tuning method's of Minimum Error Integral Criteria for determining the error values of ITAE, ISE and IAE. The time domain specifications and the performance index of different PID controller's are compared.

## 2. MATHEMATICAL MODELING OF A pH PROCESS

The pH is the measure of the acidity or alkalinity of a solution. The pH process consists of neutralization of two monophonic reagents of a weak acid and a strong base. The method implemented in this work involves mass balance on components called reaction invariants of the continuous stirred tank reactor solution. The model of the pH neutralization process used in this work is shown in Figure 1. Assumption of perfect mixing is general in the modeling of pH processes.

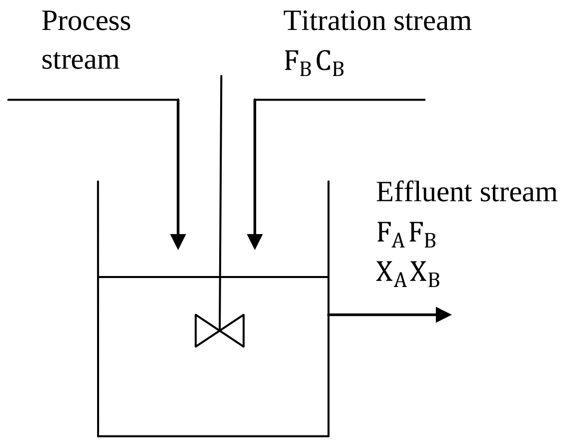


**Fig 1: pH process**

The variables shown in Figure 1 are:

$F_A$ - Flow rate of the influent stream in the CSTR

$F_B$ - Flow rate of the titrating stream in the CSTR

$C_A$ - Concentration of the influent stream in the CSTR

$C_B$ - Concentration of the titrating stream in the CSTR

$X_A$ - Concentration of the acid solution in the CSTR

$X_B$ - Concentration of the basic solution in the CSTR

V - Volume of the mixture

r - Rate of reaction per unit volume

ρ - Density

The fundamental dependent quantities are:

a. Total mass of reacting material in tank.

b. Mass of components A and B in reacting mixture.

c. Total concentration of reacting mixture in tank.

Total mass balance:

$$\frac{\begin{bmatrix}\text{Accumulation of}\\ \text{total mass}\end{bmatrix}}{\text{time}} = \frac{\begin{bmatrix}\text{input of total}\\ \text{mass}\end{bmatrix}}{\text{time}} - \frac{\begin{bmatrix}\text{output of total}\\ \text{mass}\end{bmatrix}}{\text{time}} \pm \frac{\begin{bmatrix}\text{total mass generated}\\ \text{or consumed}\end{bmatrix}}{\text{time}} \quad (2)$$

$$\frac{d(\rho V)}{dx} = \rho F_A - \rho F_B \pm 0 \quad (3)$$

Total balance of Component A:

$$\frac{\begin{bmatrix}\text{Accumulation}\\ \text{of A}\end{bmatrix}}{\text{time}} = \frac{\begin{bmatrix}\text{Input}\\ \text{of A}\end{bmatrix}}{\text{time}} - \frac{\begin{bmatrix}\text{Outpu t}\\ \text{of A}\end{bmatrix}}{\text{time}} - \frac{\begin{bmatrix}\text{Dissapearance of A}\\ \text{due to reaction}\end{bmatrix}}{\text{time}} \quad (4)$$

$$\frac{d(X_A)}{dx} = \frac{d(C_A V)}{dx} = C_A F_A - C_B F_B - rV \quad (5)$$

Total energy balance:

$$\frac{\begin{bmatrix}\text{Accumulation of}\\ \text{total energy}\end{bmatrix}}{\text{time}} = \frac{\begin{bmatrix}\text{input of total}\\ \text{energy}\end{bmatrix}}{\text{time}} - \frac{\begin{bmatrix}\text{output of total}\\ \text{energy}\end{bmatrix}}{\text{time}} - \frac{\begin{bmatrix}\text{energy removed}\\ \text{by collant}\end{bmatrix}}{\text{time}} \quad (6)$$

The shaft work done by the impeller of the stirring mechanism has been neglected. Hence the total energy (E) of the reacting mixture is

$$E = U + K + P_{energy} \quad (7)$$

Where U - Internal energy

K - Kinetic energy

$P_{energy}$ - Potential energy

Characterized total mass:

The density will be a function of concentration $C_A$ and $C_B$ and the temperature T. Quite often the dependence of d on $C_A$, $C_A$ and T is weak and the density can be considered constant as the reaction proceeds. Therefore Equation (3) becomes

$$\frac{d(\rho V)}{dt} = \rho \frac{dV}{dt} \quad (8)$$

Characterize the Mass of Component A:

From Equation (5) the state variables needed are $C_A$ and V. The algebraic manipulation on it gives

$$\frac{dC_A}{dx} = \frac{F_A}{V}(C_A - C_B) - k_0 e^{-E_1/RT} C_A \quad (9)$$

where $k_0$ – constant

R – reaction rate

$E_1$ – energy constant

$$R - k_0 e^{-E1/RT} C_A \quad (10)$$

Characterize the total concentration:

The obtained equations are

$$\frac{d(X_A)}{dt} = \frac{d(C_A V)}{dt} = C_B F_B - C_A F_A - rV \quad (11)$$

$$\frac{d(X_B)}{dt} = \frac{d(C_B V)}{dt} = 0 - C_B F + rV \quad (12)$$

The formula for determining the pH of a solution is

$$pH = -\log_{10}[H^+] \quad (13)$$

where pH has a logarithmic relationship with the molar concentration of $[H^+]$, whether acidic or basic and hence $[H^+]$ is the negative of anti logarithmic value of pH.

The above mathematical equations describe how the concentration of the acidic and basic components, $X_A$ and $X_B$ change dynamically with time subject to the input streams, $F_A$ and $F_B$.

Linearizing using Taylor series method the obtained transfer function is shown in the Equation (14)

$$G_p(s) = \frac{e^{-LS}}{(1+s)(1+0.1s)^2} \quad (14)$$

where L is the delay time in second of the process [2].

## 3. EXPERIMENTAL SETUP

This experiment is conducted at the Advanced Process Control Laboratory, Sri Ramakrishna Engineering College, Coimbatore, Tamilnadu, India using bench scale pH process station. An acid stream (HCl solution) and an alkaline stream (NaOH) with 0.1 normality is fed to a 5 litres constant volume stirrer tank and the pH is measured through pH transmitter (glass electrode) which is placed at the tank. The main objective of the system is to maintain the specific pH value by variations in base flow rate and keeping the acid flow rate at a constant level.

The acid flow rate is kept at a constant level and a step change is given to the base flow rate and the computer is interface with the data acquisition and control and use the MATLAB simulation toolbox to obtain the first order plus dead time transfer function model.

$$G(s) = \frac{K_p e^{-t_d s}}{\tau s+1} = \frac{0.34811\, e^{-0.576 s}}{0.17416 s+1} \quad (15)$$

where $K_p$ - Proportional gain, $\tau$ – Integral time, $t_d$ – Delay time

## 4. CONVENTIONAL CONTROLLERS

### 4.1 Proportional - Integral Controller

PI controller is a conventional controller used in industries. It will eliminate forced oscillations and steady state error resulting in operation of on -off controller and proportional controller respectively. It is generally used in the area where speed of the system is not an issue.

$C(s) = K_p + \frac{K_i}{s} = K_p\left(1 + \frac{1}{T_i s}\right)$

Where $K_p$ - Proportional Gain, $K_i$ - Integral Gain, $T_i$ - Reset Time $= K_p / K_i$.

The main purpose of designing a PI controller is to determine the two gains, such as proportional gain ( $K_p$), integral gain ($K_i$) [3, 4].

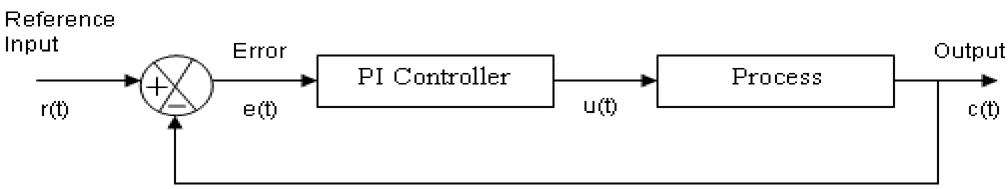


**Fig 2:Block Diagram of PI Controller**

The first widely used method for PID tuning was published by Ziegler-Nichols in 1942. Different methods are used for the tuning of PI controllers. The two categories of PID tuning methods are Open loop method and Closed loop method. Ziegler Nichols closed loop tuning technique was perhaps the first rigorous method to tune PID Controllers. The technique is not widely used today because the closed loop behaviour tends to be oscillatory and sensitive to uncertainty. Ziegler Nichols also proposed tuning parameter for the process that has been identified as first order plus time delay process have a maximum slope of $K = K_p / \tau$ at $t = t_d$ for a unit step input changes [4].

The obtained gain values of PI controller based on Ziegler Nichols Closed loop Oscillation methodis

$k_c = 0.157$

$\tau_i = 0.146$

The Simulink model for conventional PI controller is shown in Figure 3.

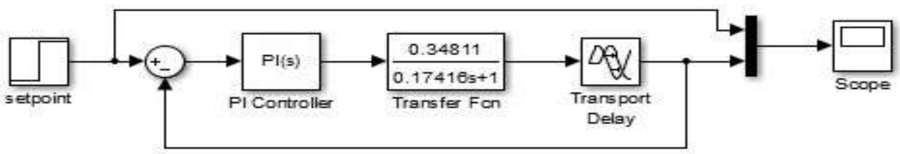


**Fig3:Simulink model for conventional PI controller**

PI and PID controller tuned using Ziegler Nichols tuning procedure. The tuning parameters are shown in Table 1 and 2.

**Table 1. Ziegler Nichols Closed loop Oscillation method tuning parameters**

| Controller | $k_c$ | $\tau_i$ | $\tau_d$ |
|---|---|---|---|
| **P** | $0.5K_p$ | - | - |
| **PI** | $0.45K_p$ | $\frac{\tau}{1.2}$ | - |
| **PID** | $0.6K_p$ | $\frac{\tau}{2}$ | $\frac{\tau}{8}$ |

**Table 2.Ziegler Nichols Open loop tuning parameters**

| Controller | $k_c$ | $\tau_i$ | $\tau_d$ |
|---|---|---|---|
| **P** | $\frac{\tau}{K_p t_d}$ | - | - |
| **PI** | $\frac{0.9\tau}{K_p t_d}$ | $3.3t_d$ | - |
| **PID** | $\frac{1.2\tau}{K_p t_d}$ | $2t_d$ | $0.5t_d$ |

## 4.2 Proportional – Integral - Derivative Controller

The PID form of controller has been used successfully in the process industries since the 1940s and remains the most widely used algorithm today for a very wide range of applications. The success of this type of controller is due to the fact that the PID control algorithm is very simple in structure, the controller is relatively easy to design for most applications and has properties that make it much more straightforward to understand in simple physical terms than many other forms of controller.A proportional integral derivative controller (PID controller) is a control loop feedback mechanism (controller) widely used in industrial control systems. A PID controller calculates an error value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process through us of a manipulated variable. The PID controller algorithm involves three separate constant parameters, and is accordingly sometimes called three-term control: the proportional, the integral and derivative values, denoted P, I and D. Simply put, these values can be interpreted in terms of time: P depends on the present error, I on the accumulation of past errors, and D is a prediction of future errors, based on current rate of change [5].

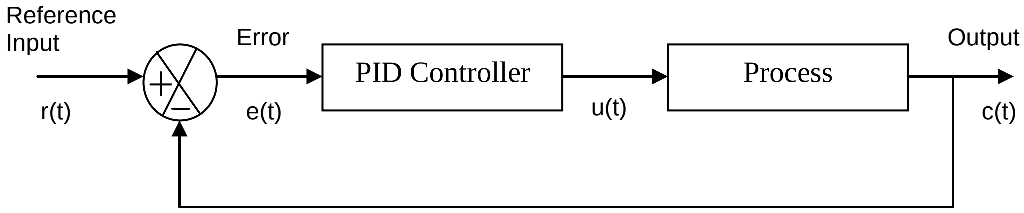


**Fig 4: Block Diagram of PID Controller**

The obtained gain values of PID controller based on Ziegler Nichols Closed loop Oscillation methodis

$K_c$ = 0.208; $\tau_i$ = 0.087; $\tau_d$ = 0.022

The Simulink model for conventional PID controller is shown in Figure 5

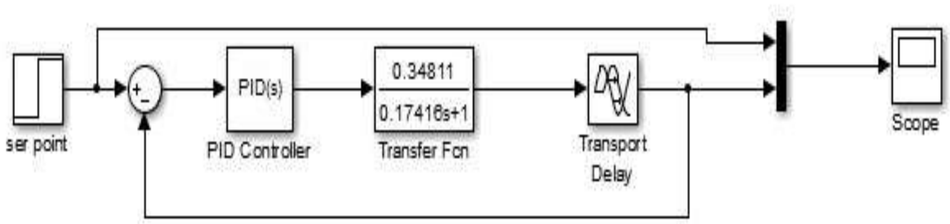


**Fig 5: Simulink model for conventional PID controller**

### 4.3 Tyreus – Luyben Method

This is a more conservative approach than Ziegler-Nicholas method and so it gives better performance with small values for dead time. But when the value of dead time is large it gives a sluggish performance. It considers ultimate gain Ku and frequency Pu for tuning the controller [6].The Tyreus-Luyben procedure is quite similar to the Ziegler–Nichols method but the final controller settings are different. Like Z-N method this method is time consuming and forces the system to margin if instability. The tuning parameters for Tyreus-Luyben are shown in Table 3.

**Table 3 Tuning parameters of Tyreus-Luyben**

| Controller | $k_c$ | $\tau_i$ | $\tau_d$ |
|---|---|---|---|
| PI | $\frac{K_p}{3.2}$ | $2.2\tau$ | - |
| PID | $\frac{K_p}{2.2}$ | $2.2\tau$ | $\frac{\tau}{6.3}$ |

The obtained gain values of PID controller based on Tyreus-Luyben method is

$K_c = 0.158$;  $\tau_i = 0.383$;  $\tau_d = 0.028$

The Simulink model for PID controller based on Tyreus Luyben is shown in Figure 6

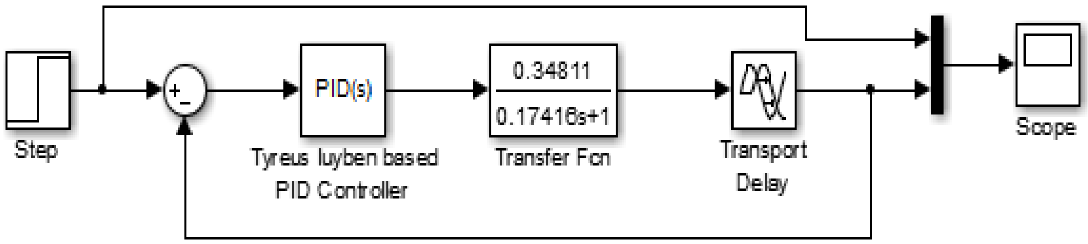


**Fig 6:Simulink model for PID controller based on Tyreus Luyben**

### 4.4 IMC based tuning for PID controller

Model based control systems are helpful to achieve desired set points and reject small external disturbances. The internal model control (IMC) design is based on the fact that control system contains the process to be controlled then a perfect control can be achieved.

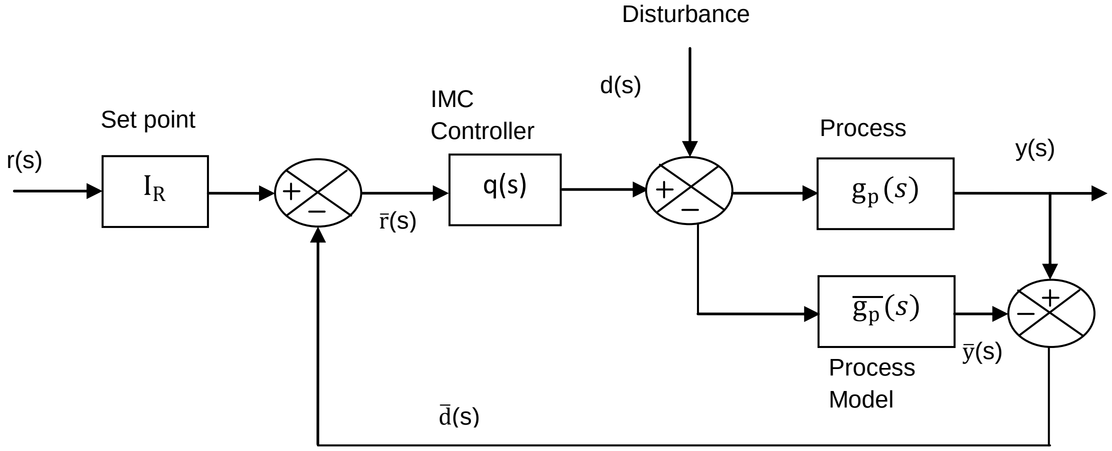


**Fig 7:IMC structure**

A feedback equivalent is developed to IMC from the Figure 7 using block diagram manipulation q(s). The controller $g_p(s)$represents the actual process and the $\bar{g}_p(s)$represents the model of the process [3].

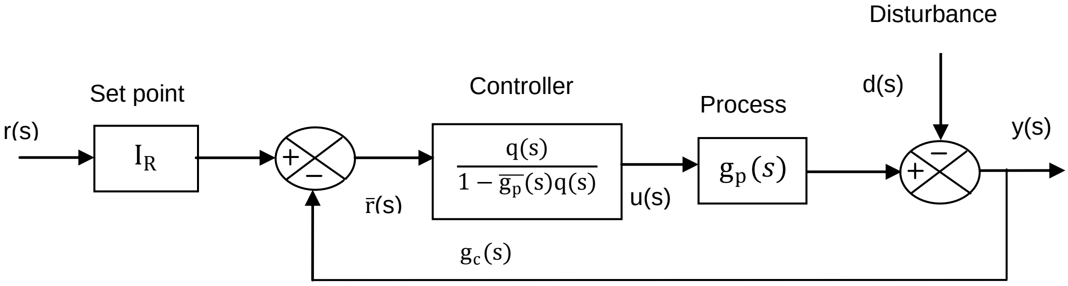


**Fig 8: Standard feedback Equivalent to IMC**

The standard feedback controller which is equivalent to IMC is

$$g_c(s) = \frac{q(s)}{1-\overline{g}_p(s)q(s)} \tag{16}$$

To derive PID equivalent form for processes with a time-delay, where some approximation to the dead time is made, so that first-order Pade approximation for dead time is taken.

$$g_p(s) = \frac{k_p}{\tau s+1} e^{-t_d s} \tag{17}$$

$$e^{-t_d s} = \frac{1-\frac{t_d s}{2}}{1+\frac{t_d s}{2}} \tag{18}$$

$$g_p(s) = \frac{0.34811(1-0.288s)}{(0.17416s+1)(1+0.288s)} \tag{19}$$

IMC controller transfer function, q(s)

q(s) = $\overline{q}$(s) f(s)

$$q(s) = \frac{(0.17416s+1)(1+0.288s)}{0.34811} \frac{1}{\lambda s+1} \tag{20}$$

$$\text{Where } \overline{q}(s) = \frac{(0.17416s+1)(1+0.288s)}{0.34811} \tag{21}$$

$$f(s) = \frac{1}{\lambda s+1} \tag{22}$$

$\lambda$ = Filter Tuning Parameter

Equivalent standard feedback controller using the transformation

$$g_c(s) = \frac{\overline{q}(s)f(s)}{1-\overline{g}_{p+}(s)f(s)} \tag{23}$$

$$g_c(s) = \frac{1}{0.34811}\left[\frac{0.05015808\,s^2+0.46216s+1}{(\lambda+0.288)s}\right] \tag{24}$$

Here $\lambda > 0.8t_d$

$\lambda$=0.5

The obtained gain values of tuning PID controller based on IMC method are

$k_c$ = 1.685

$\tau_i$ = 0.462

$\tau_d$ = 0.108

The simulink model for IMC based PID controller is shown in Figure 9.

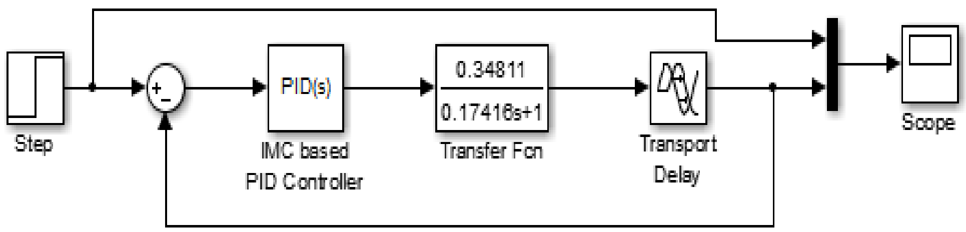


**Fig 9:Simulink model for IMC based PID controller**

## 4.5 Direct Synthesis method

In general, both the direct synthesis and IMC methods do not necessarily result in PID controllers. However, by choosing the appropriate desired closed-loop response and using either a Pade approximation for the time delay, PID controllers can be derived for process models that are commonly used in industrial applications.The direct synthesis methods for PID controllers are typically based on a time-domain or frequency-domain performance criterion [10]. The controller design is based on a desired closed-loop transfer function. Then, the controller is calculated analytically so that the closed-loop set-point response matches the desired response. The obvious advantage of the direct synthesis approach is that performance requirements are incorporated directly through specification of the closed-loop transfer function [11].

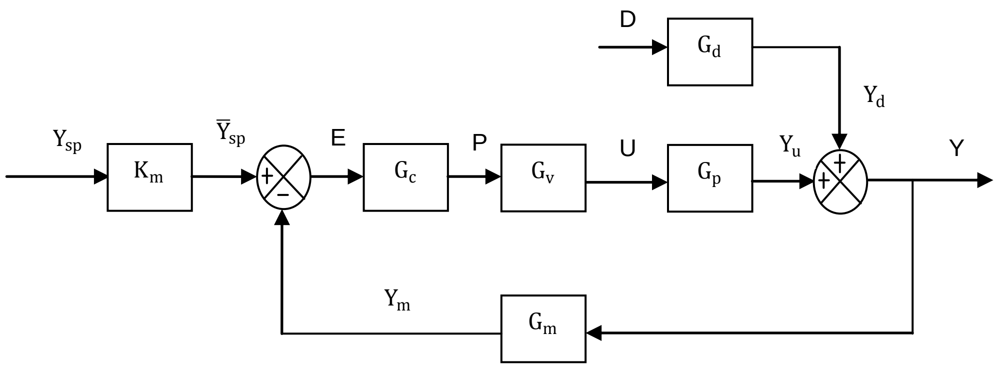


**Fig 10: Block diagram for a standard feedback control system**

$$\frac{Y}{Y_{sp}} = \frac{K_m G_c G_v G_p}{1+G_c G_v G_p G_m} \quad (25)$$

For simplicity let $G \triangleq G_v G_p G_m$

$$\frac{Y}{Y_{sp}} = \frac{G_c G}{1+G_c G} \quad (26)$$

$$G_c = \frac{1}{G}\left(\frac{\frac{Y}{Y_{sp}}}{1-\frac{Y}{Y_{sp}}}\right) \quad (27)$$

The above equation cannot be used for controller design because the closed-loop transfer function $\frac{Y}{Y_{sp}}$ is not known a priori. Also it is used to distinguish between the actual process G and the model $\overline{G}$ that provides an approximation of the process behaviour. A practical design equation can be derived by replacing the unknown G by $\overline{G}$ and $\frac{Y}{Y_{sp}}$ by a desired closed loop transfer function $\left(\frac{Y}{Y_{sp}}\right)_d$

$$G_c = \frac{1}{\overline{G}}\left(\frac{\left(\frac{Y}{Y_{sp}}\right)_d}{1-\left(\frac{Y}{Y_{sp}}\right)_d}\right) \quad (28)$$

The specification of $\left(\frac{Y}{Y_{sp}}\right)_d$ is the key design decision and will be considered. Note that the controller transfer function in Equation (28) contains the inverse of the process model owing to the $\frac{1}{\overline{G}}$ term.

### 4.5.1 Desired closed loop transfer function

For process without time delay the first order model in Equation (28) is a reasonable choice.

$$\left(\frac{Y}{Y_{sp}}\right)_d = \frac{1}{\tau_c s+1} \quad (29)$$

By substituting Equation (29) in Equation (28) and solving for $G_c$ the controller design equation becomes

$$G_c = \frac{1}{\overline{G}}\frac{1}{\tau_c s} \quad (30)$$

The $\frac{1}{\tau_c s}$ term provides integral control action and thus eliminates offset.

Design parameter $\tau_c$ provides a continuous controller tuning parameter that can used to make the controller more aggressive (small$\tau_c$) or less aggressive (large$\tau_c$).

If the process transfer function contains a known time delay $t_d$ , a reasonable choice for the desired closed-loop transfer function is

$$\left(\frac{Y}{Y_{sp}}\right)_d = \frac{e^{-t_d s}}{\tau_c s+1} \quad (31)$$

The time-delay term in Equation (31) is essential because it is physically impossible for the controlled variable to respond to a set-point change at t= 0, before t=$t_d$. If the time delay is unknown,$t_d$ must be replaced by an estimate.

Combining Equation (31) and Equation (28) gives

$$G_c=\frac{1}{G}\frac{e^{-t_d s}}{\tau_c s+1-e^{-t_d s}} \quad (32)$$

The Equation (32) can be used to derive PID controllers for simple process models. The following derivation is based on approximating the time delay term in the denominator of Equation (32) with a truncated Taylor series expansion

$$e^{-t_d s} = 1-t_d s \quad (33)$$

Substituting Equation (33) into the denominator of Equation (32) and rearranging gives

$$G_c=\frac{1}{G}\frac{e^{-t_d s}}{(\tau_c+t_d)s} \quad (34)$$

### 4.5.2 First-Order-plus-Time-Delay (FOPTD) Model for Direct Synthesis

First-Order-plus-Time-Delay (FOPTD) Model,

$$\overline{G}(s)=\frac{k\,e^{-t_d s}}{\tau_c s+1} \quad (35)$$

Substituting Equation (35) into Equation (34) and rearranging gives a PID controller,

$$G_c=\frac{\tau s+1}{k(\tau_c+t_d)s} \quad (36)$$

The obtained gain values of tuning PID controller based on Direct synthesis method are

$$k_c = \frac{\tau}{k_p(\tau_c+t_d)} = \frac{0.17416}{0.34811(0.5+0.576)} = 1.737$$

$$\tau_i = \tau = 0.174$$

$$\tau_d = \frac{t_d}{2} = \frac{0.576}{2} = 0.288$$

The Simulink model for Direct Synthesis based PID controller is shown in Figure 11.

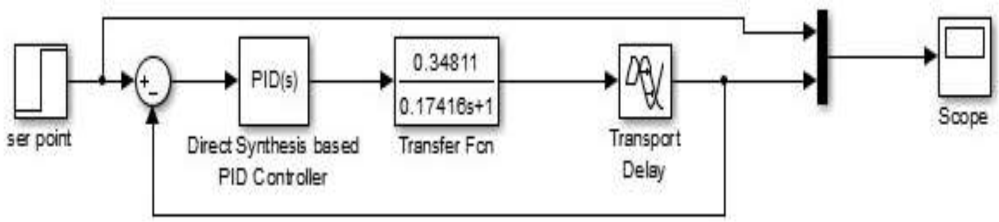


**Fig 11:Simulink model for Direct Synthesis based PID controller**

## 5. RESULTS AND DISCUSSIONS

Investigation of ZN-PI, ZN-PID, Tyreus Luyben-PID, IMC-PID and Direct Synthesis-PID controllers for laboratory scale pH neutralization process system is described in this section. For this investigation the acid (HCl) and base (NaOH) is fed in to the mixing tank and the flow is controlled through the control valve which is controlled by PID controller. Here the pH value of the effluent is maintained at different set values (4, 7 and 11 for acid, neutral and base region respectively) as shown in figure 12, 13 and 14 respectively. The comparative closed loop response of proposed controller is shown in the Figure 12, 13 and 14 for acid, neutral and base regions based on the controller design.

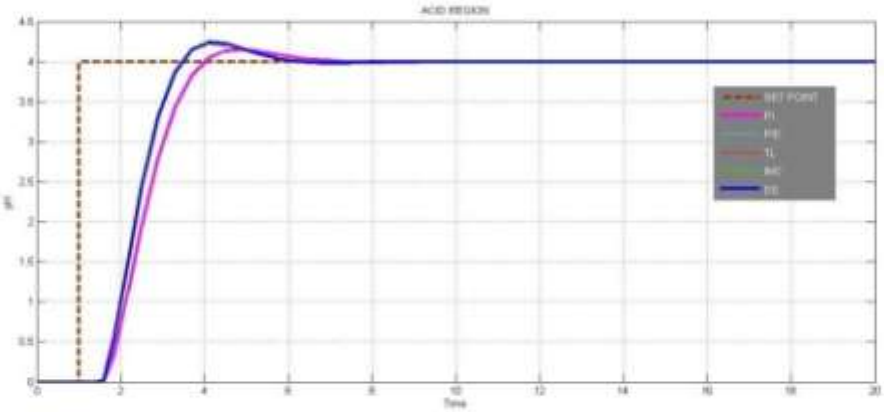


**Fig 12:Response of the controllers in Acid region (pH = 4)**

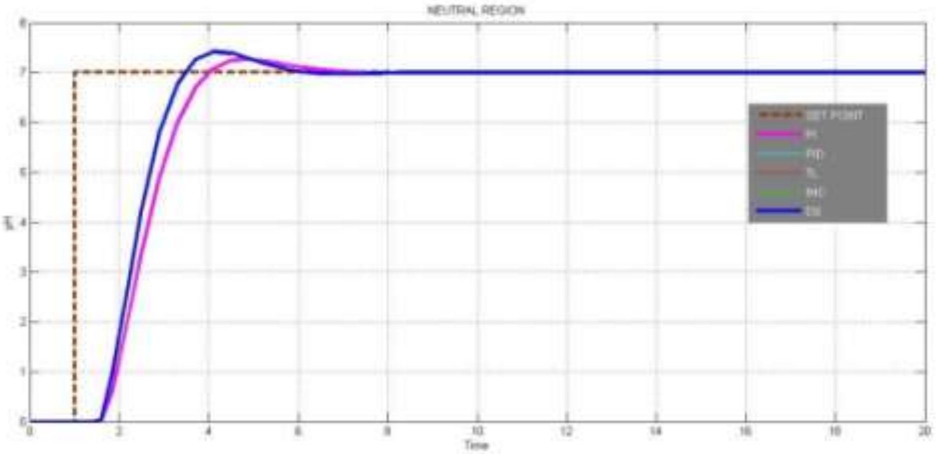


**Fig 13:Response of the controllers in Neutral region (pH = 7)**

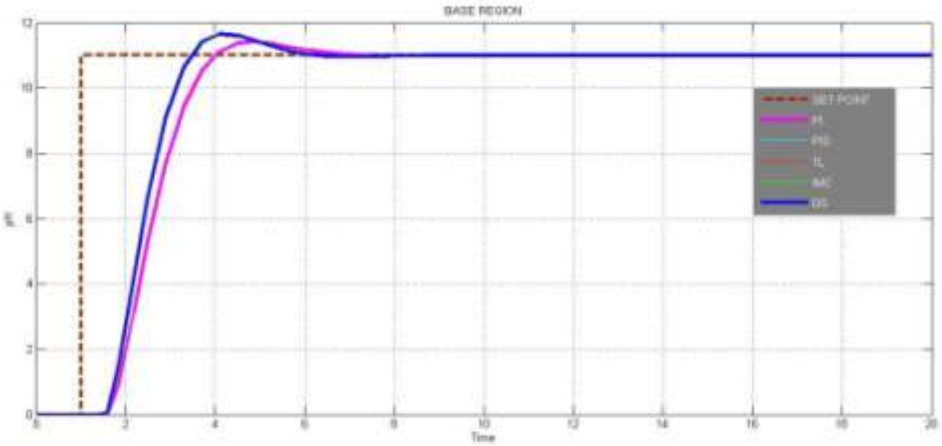


**Fig 14:Response of the controllers in Base region (pH = 11)**

The comparative analysis of controller performance based on the rise time, settling time, peak time, peak overshoot are identified and listed in table 4.The error indices like Integral Absolute Error (IAE) and Integral Square Error (ISE) are also calculated and tabulated in Table 4 of the proposed system.

**Table 4. Comparative performance metrics of Conventional PI, PID, Tyreus-Luyben, IMC based PID and Direct Synthesis method.**

| Controller | Region | Rise time (sec) | Peak time (sec) | Delay time (sec) | Settling time (sec) | IAE | ISE |
|---|---|---|---|---|---|---|---|
| | Acid | 4.05 | 4.89 | 2.53 | 9.90 | 2.53 | 2.26 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Conventional PI controller | Neutral | 4.05 | 4.89 | 2.53 | 9.90 | 2.53 | 2.26 |
| | Base | 4.05 | 4.89 | 2.53 | 9.90 | 2.53 | 2.26 |
| Conventional PID controller | Acid | 3.48 | 4.24 | 2.35 | 8.55 | 2.30 | 2.12 |
| | Neutral | 3.48 | 4.24 | 2.35 | 8.55 | 2.30 | 2.12 |
| | Base | 3.48 | 4.24 | 2.35 | 8.55 | 2.30 | 2.12 |
| Tyreus Luyben | Acid | 3.48 | 4.25 | 2.34 | 11.20 | 2.30 | 2.12 |
| | Neutral | 3.48 | 4.25 | 2.34 | 11.20 | 2.30 | 2.12 |
| | Base | 3.48 | 4.25 | 2.34 | 11.20 | 2.30 | 2.12 |
| Internal Model Controller | Acid | 3.48 | 4.25 | 2.34 | 11.15 | 2.30 | 2.12 |
| | Neutral | 3.48 | 4.25 | 2.34 | 11.15 | 2.30 | 2.12 |
| | Base | 3.48 | 4.25 | 2.34 | 11.15 | 2.30 | 2.12 |
| Direct Synthesis | Acid | 3.48 | 4.24 | 2.35 | 11.15 | 2.30 | 2.12 |
| | Neutral | 3.48 | 4.24 | 2.35 | 11.15 | 2.30 | 2.12 |
| | Base | 3.48 | 4.24 | 2.35 | 11.15 | 2.30 | 2.12 |

## 6. CONCLUSION

The controlling of nonlinear system is a very challenging task to perform. In this work, model is obtained for pH process. By using obtained model, proper tuning values are obtained for different controllers. The pH value is controlled in simulation using various control schemes such as ZN-PI, ZN-PID, Tyreus Luyben-PID, IMC-PID and Direct Synthesis-PID controllers. By the analysing the simulation results all the PID tuning gives the same response.

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