ADAPTIVE CONTROL OF a pH PROCESS

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ABSTRACT

A control system of neutralization process in a continuous stirred tank reactor (CSTR) has been developed in this work where the dynamic and control system based on basic mass balance has been carried out.

A dynamic model for neutralization process is described by a first order with dead time; the approximate transfer function is;

$$G(s)=\frac{2.95 \ e^{-S}}{270\, s+1}$$

The responses of pH electrode were analyzed to give the first order transfer function which is:

$$G(s)=\frac{1}{0.32\, s+1}$$

The tuning of control parameters was determined by two different methods; frequency analysis method, and process reaction curve method to find the best values of proportional gain (K_c), integral time (τ_I) and derivative time (τ_D). The integral of time absolute error (ITAE) was used to compare between methods above.

Adaptive control system was used as another strategy to compare with conventional control system, good improvement in controlling of the pH neutralization process is achieved when the adaptive control is used.

MATLAB program was used as a tool of solution for all cases mentioned in this work.

Key word: Neutralization Process, Adaptive Control, Conventional Control.

1. INTRODUCTION

Control of the pH neutralization process plays an important role in different chemical plants, such as chemical and biological reaction, waste water treatment, electrochemistry and precipitation plants, production of pharmaceuticals, fermentation, food production[(1)].

However, it is difficult to control a pH process with adequate performance point due to its nonlinearities, time-varying properties and sensitivity to small disturbances when working near the equivalence point[(2)].

For most industrial pH neutralization processes the influent stream is formed from the merging of effluents from many different plants each containing a variety of chemical species. The concentrations of the species in the resulting stream vary with time and hence the titration curve changes [(3)].

Continuous control systems are used when waste water is continuously being generated and generally one work day worth of flow is too large to be effectively captured in a batch system storage tank. As with batch control good mixing and safety precautions are very important, but also automatic reagent addition and continuous pH recording is required. The time required for influent flow to reach the probe is an important factor for properly setting the reagent feed control rate. By the time the added reagent reaches the sensor does not measure large variations in pH [(4)].

2. CONTROL METHODS

Conventional control theory deals predominantly with linear systems having constant parameters. This is often a good approximation for systems that are regulated at fixed operating points. With moderate disturbances and a good control system the deviations will be so small that the linear approximation is sufficiently good. However, the linear constant coefficient approximation will not always be satisfactory when the operating conditions change. However, an adaptive control for example can be designed to overcome the limitations of conventional control systems [(5)].

The PID controller still does not satisfy the industrial demand for acceptable pH control in process streams in chemical plants or treatment of waste streams. The pH control process, therefore, demands the application of control theory taking into account the nonlinearity and the time varying titration curve.

The attention, therefore, has been focused on the application of more advanced control techniques like adaptive and self-tuning controllers. Adaptive control with linear feedback if we do not consider nonlinearity to be a major problem. Adaptive control with nonlinear feedback if we consider the richer model structure of a nonlinear model to have better prerequisites to adapt itself to the measured data [6].

2.1 Adaptive Control

Adaptive is called a control system, which can adjust its parameters automatically in such a way as to compensate for variations in the characteristics of the process it controls. The various types of adaptive control systems differ only in the way the parameters of the controller are adjusted.

There are two main reasons for using adaptive control in chemical process:

1. Most chemical process is nonlinear. Therefore, the linearized models that are used to design linear controllers depend on the particular steady state. It
2. Most of the chemical process are non stationary (i.e. their characteristics change with time).

The adaptive control needs an objective function that will guide the adaptation mechanism to the "best" adjustment of the controller parameters. Any of the performance criteria could be used as:

- One-quarter decay ratio.
- Integral of the square error (ISE).
- Gain or phase margins, etc.

There are two different mechanisms for the adaptation of the controller parameters:

a. Programmed or Scheduled Adaptive Control

b. Self- Adaptive Control

Model Reference Adaptive Systems (MRAS) are one popular adaptive control scheme currently used. These schemes rely on the creation of an exact mathematical model of the process for each application of the controller. It requires a detailed knowledge of the transfer function (plant order, time constants, dead time), usually determined experimentally.

The proposed adaptive control in this work is based on the principle of model reference adaptive control.

The gain of the main control algorithm is altered by a superposed adaptive control loop so that, in the case of a control deviation, the pH value of the effluent approaches its setpoint by a prescribed trajectory. This is controlled by comparing the actual speed of the control deviation with the reference speed given by the reference trajectory. The reference speed is calculated depending on the control deviation. The adaptive control system is represented in Fig. (1).

A multi-model adaptive PID controller is developed and evaluated in a simulation study For a nonlinear pH neutralization process. The performance and robustness characteristics of the multi-model controller are compared to those for conventional PID controllers and an alternative "multi-model interpolation" controller [7].

The use of a multi-model adaptive PID controller is developed and evaluated in an experimental study using a nonlinear pH neutralization process.. The performance and robustness characteristics of the multi-model controller are compared to those of a conventional PID controller, conventional self-tuning controller, and a multi-model adaptive PID controller using a prediction of error criterion [8].

3. REACTOR PROCESS

The process can be considered as a continuous stirred tank reactor (CSTR) to neutralize a strong acid with a strong base manipulated by a control valve. The process consists of an influent stream (HCl), reagent stream (NaOH) to regulate the pH of the effluent stream, and an effluent stream. A schematic diagram is shown in Fig. (2). The data of this reaction was taken from a previous experimental work by Syafiie et al., 2006 [9], this data is shown in table (1).

3.1 Model for Strong Acid-Strong Base System

Consider a stirred tank into which hydrochloric acid of concentration [HCl] flows into the tank at a rate F_a (influent stream) and is neutralized by sodium hydroxide of concentration [NaOH] flows at a rate F_b (reagent). The volume of the reacting mixture in the tank is constant and equal to V.

The chemical reaction of these two solutions occurring in the stirred tank reactor is

$$NaOH + HCl + H_2O \rightarrow H_2O + Cl^- + Na^+ + H^+ + OH^-$$

Thus, the ionic concentrations of $[Cl^-]$ and $[Na^+]$ in the outflow from the tank would be related to the total flows F_a, F_b and to the feed concentrations of strong acid [HCl] and strong base [NaOH] entering the tank. Hence, the mass balances on this strong acid and strong base component are:

$$V\frac{d[Cl^-]}{dt}=[HCl]F_A-(F_A+F_B)[Cl^-] \quad (1)$$

$$V\frac{d[Na^+]}{dt}=[NaOH]F_B-(F_A+F_B)[Na^+] \quad (2)$$

From charge balance:

$$[Na^+] + [H^+] = [Cl^-] + [OH^-] \quad (3)$$

or

$$[Cl^-] - [Na^+] = [H^+] - [OH^-] \quad (4)$$

Subtraction equation (3) from (4) to get:

$$V\frac{dG}{dt} = -(F_A + F_B)G + C_A F_A - C_B F_B \quad (5)$$

Where:

G = the distance from neutrality and is given by $G=[H^+]-[OH^-]$

V = the tank volume

C_A = the concentration of acid

C_B = the concentration of base

F_A = the flow rate of acid

F_B = the flow rate of base.

The value of G is zero at neutral point, pH=7. The measurement equation is derived as follows:

$$pH = -\log_{10}[G + (G^2 + 4K_w)^{0.5}] + \log_{10} 2 \quad (6)$$

where $K_w = 10^{-14}$ $(mol/l)^2$ is taken. The high nonlinearity is introduced by this output equation between the measurement pH value and state G [10].

4. RESULT AND DISCUSSION

In this work, dynamic models have been developed to study the influence of manipulated variable (F_B) on controlled variable (pH) of the process.

The results include two main parts:

1. The first part is to study the open loop system (without control) where the transfer functions were computed by using state space model as follows:

   a. Transfer function between the controlled variable and manipulated variables are:

   - Transfer function between flow rate of base (F_B) and controlled variable (pH)

     A= [-0.0037] B= $\left[-0.005*10^{-6}\right]$ C= $\left[-2.1715\times10^{6}\right]$

   - Transfer function between concentration of base (C_B) and controlled variable (pH)

     A= [-0.0037] B= $\left[-0.0018\right]$ C= $\left[-2.1715\times10^{6}\right]$

   b. Transfer functions between the controlled variable and disturbance variables are:

   - Transfer function between flow rate of acid (F_A) and controlled variable (pH)

     A= [-0.0037] B= $\left[0.005*10^{-6}\right]$ C= $\left[-2.1715\times10^{6}\right]$

   - Transfer function between concentration of acid (C_A) and controlled variable (pH)

     A= [-0.0037] B= $\left[0.0018\right]$ C= $\left[-2.1715\times10^{6}\right]$

   c. Then the step responses are plotted and the stability of the open loop system is determined by finding the roots of the characteristic equations.

2. The second part is to study the closed loop system which is the main aim of this work through applying different control strategies.

4.1 Stability Analysis of the Closed Loop

After applying different methods to the control tuning, stability of the closed loop must be studied.

The stability analysis of the closed loop system is implemented by using the computer program simulation. Table (3) gives the roots of characteristic equation of the (CSTR) reactor of pH neutralization process.

As shown in Table (3), this table shows that the system is stable in this work where all values for PI and PID controllers gave negative sign of the real part of the roots of the characteristic equations.

4.2 Adaptive Control

In this section, the adaptive control is discussed. Adaptive controller was applied using PI and PID adaptive controller modes for the continuous stirred tank reactor (CSTR) of pH neutralization process, the minimum integral of the time-weighted absolute error (ITAE) values for PI and PID adaptive controllers are given in Table (2).

From this table, it is clear that the PI adaptive controller is better than PID adaptive controller where the value of ITAE of the first controller is smaller than the second controller.

Fig. (3) shows the comparison between transient response of PI and PID adaptive controllers while Fig. (4) shows the comparison between time × absolute error versus time for this case.

As shown in Figs. (3) and (4), it is clear that the two modes are used in adaptive control, the responses in the Fig. (3) show the good improvement in controlling of the pH process by shortening time to reach the pH set point and minimal overshoot. In those figures, it can seen that response PI adaptive is better than PID adaptive with lower settling and gives the smaller area under the curve.

4.3 Comparison between Feedback and Adaptive Controllers

Fig. (5) shows the comparison between the transient response for PID controller and PID adaptive controller.

Fig. (6) shows the comparison between the transient response for PID controller and PI adaptive controller.

Fig. (7) shows the comparison between the transient response for PI controller and PID adaptive controller.

Fig. (8) shows the comparison between the transient the integral of the time-weighted absolute error (ITAE) values for Comparisons between feedback control and adaptive control are given in Table (4).

As shown in Figs (3) to (8), it is clear that good improvement is achieved when the adaptive control is used compared to the feedback control, where (ITAE) value is the lowest and the responses reach the steady state in less time with minimal overshoot, so its more effective than using feedback control.

5. CONCLUSIONS

The present work represents a simulation programs in MATLAB language used to study and develop a mathematical model of the dynamic behavior of neutralization process in a continuous stirred tank reactor (CSTR), and the process control implemented using different control strategies. The following conclusions can be drawn:

1. The dynamic response of the mixing tank is described by a first order differential equation whose time constant is the vessel residence time. The approximate transfer function is:

$$G(p)=\frac{pH}{F_B}=\frac{2.95\ e^{-S}}{270s+1}$$

2. A first order response system is an adequate model for a glass membrane electrode. The approximate transfer function describing the pH electrode is:

$$G(S)=\frac{1}{0.32\,s+1}$$

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NOMENCLATURE

Symbol	*Definition*	*Units*
ITAE	The integral of time weight absolute error	
K_c	Proportional gain	[ml/s]
τ_I	Integral time	[sec]
τ_D	Derivative time	[sec]
C_A	Concentration of acid	[mole/ml]
C_B	Concentration of base	[mole/ml]
F_A	Volumetric flow rate of acid	[cm^3 /sec]
F_B	Volumetric flow rate of base	[cm^3/sec]
$F_A(s)$	Transfer function of acid	[cm^3 /sec]
$F_B(s)$	Transfer function of base	[cm^3 /sec]
G	The distance from neutrality and is given by $G=[H^+]-[OH^-]$	[–]
pH	The negative logarithm of the hydrogen ion concentration in aqueous solution	[–]

Table (1) Operating parameters

Strong acid flow	F_A	1.8333 ml/sec
Strong base flow	F_B	1.8333 ml/sec
Acid concentration	C_A	$1*10^{-6}$ mol/ml
Base concentration	C_B	$1*10^{-6}$ mol/ml
Tank volume	V	1000 ml
Pressure	P	1 Atm.
Temperature	T	25^0C

Table (2) ITAE values for PI and PID *adaptive controllers.*

Controllers	ITAE
PI adaptive controller	90.943
PID adaptive controller	102.649

Table (3) The Roots of Characteristic equation of (CSTR) reactor of pH neutralization process.

Control Tuning Methods	*PI mode*	*PID mode*
Frequency Analysis	-3.7178 + 2.1625i -3.7178 -2.1625i -1.5125 -0.0903+0.2350i -0.0903 -0.2350i	-5.9963 -1.7601+1.6199i -1.7601 - .6199i -0.0755+0.3253i -0.0755 -0.3253i
Process Reaction Curve	-4.3065 + 3.0995i -4.3065 -3.0995i -0.0491+0.9084i -0.0491 -0.9084i -0.4175	-7.6352 -1.9290 -0.0884+1.2558i -0.0884 -1.2558i -0.8308

Table (4) Comparisons between feedback control and adaptive control

Controllers	ITAE
PID	120.295
PI	106.2566
PID adaptive	102.649
PI adaptive	90.943

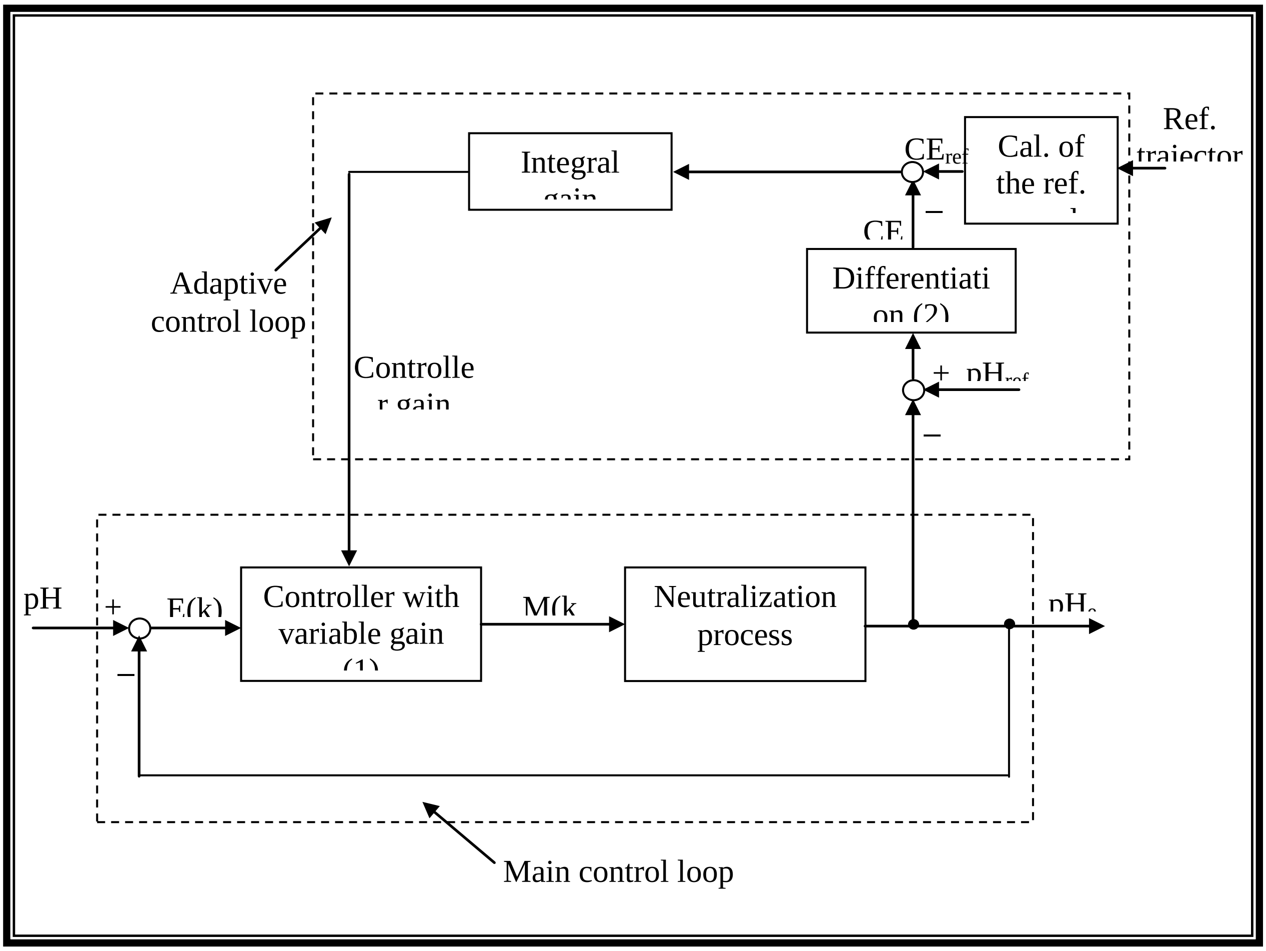

Fig. (1) Schematic representation of the adaptive control system [9].

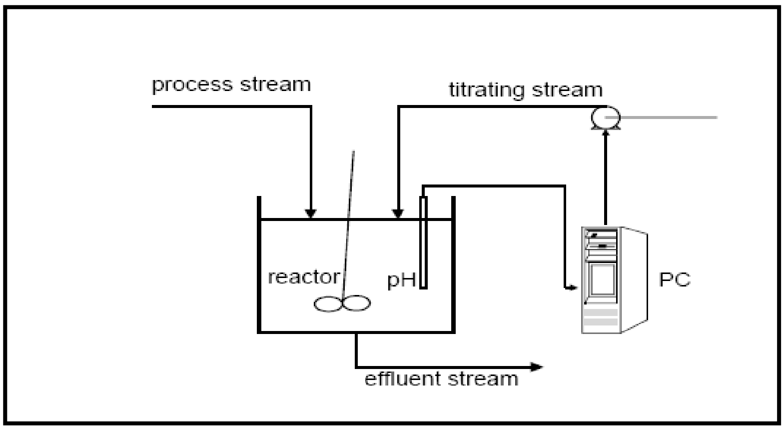

Fig. (2) pH Neutralization Process.

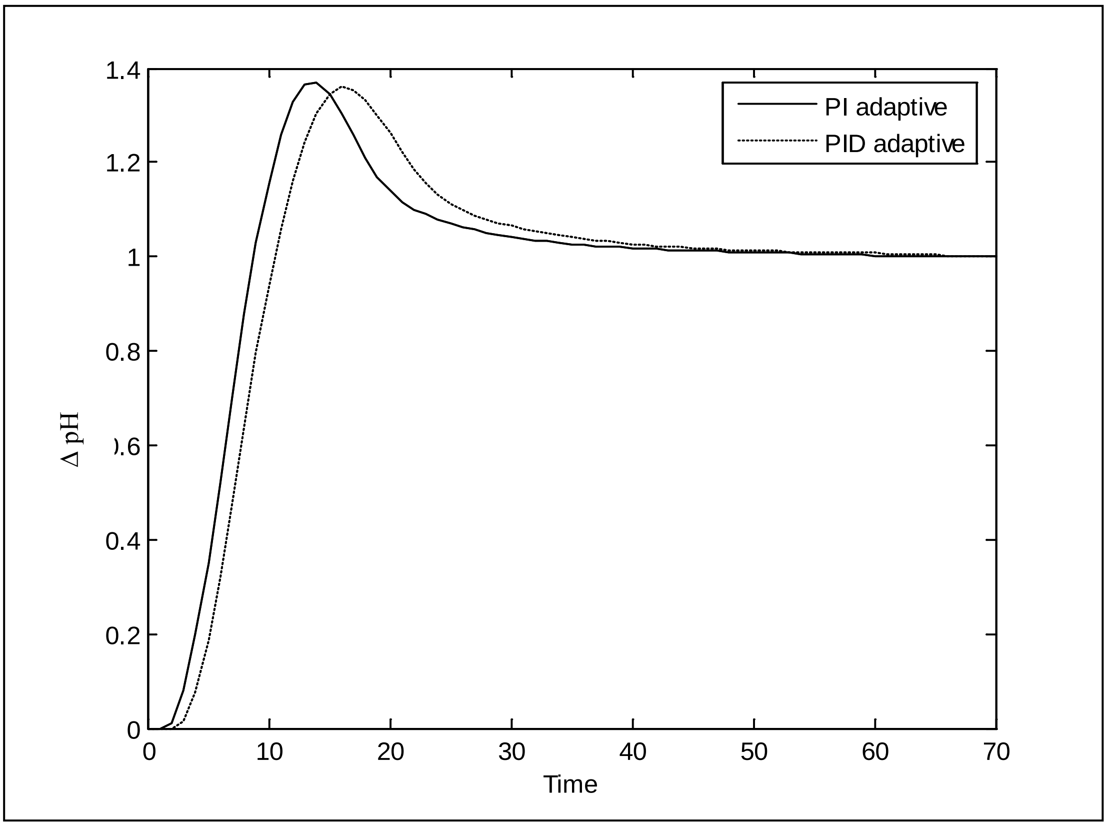

Fig. (3) The comparison between the transient response for PI adaptive and PID adaptive controllers

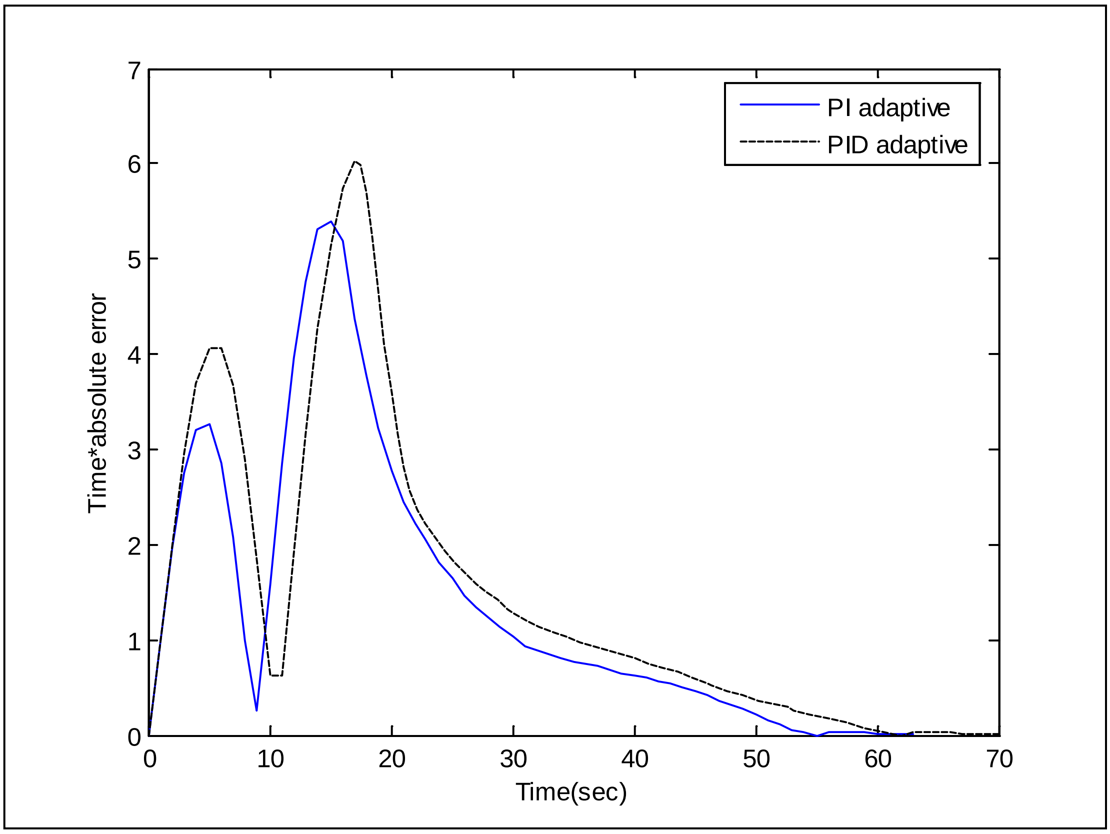

Fig. (4) Time $\times$absolute error versus time

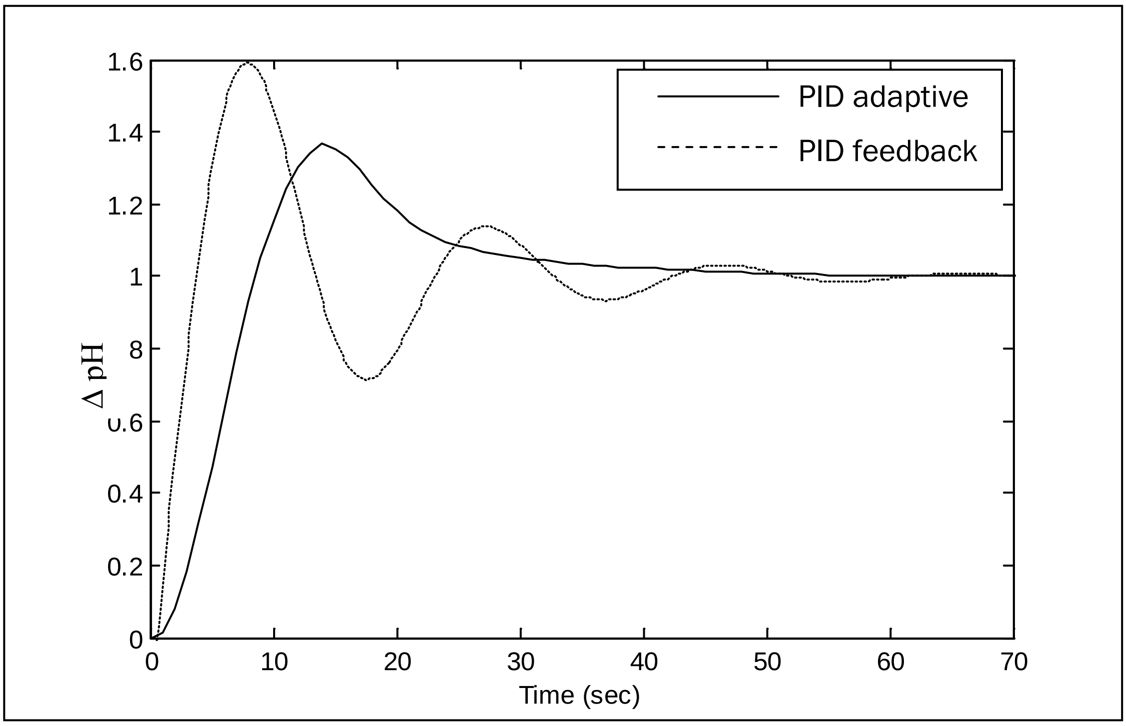

Fig. (5) The comparison between the transient response for PID feedback controller and PID adaptive controller

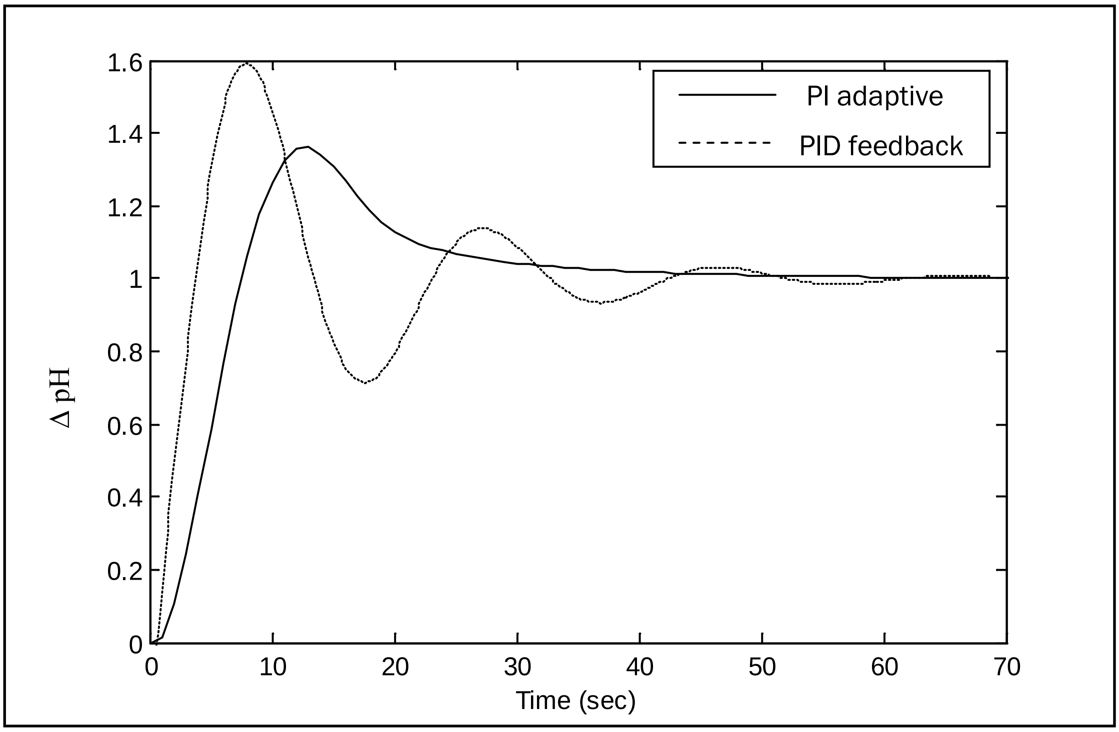

Fig. (6) The comparison between the transient response for PID feedback controller and PI adaptive controller

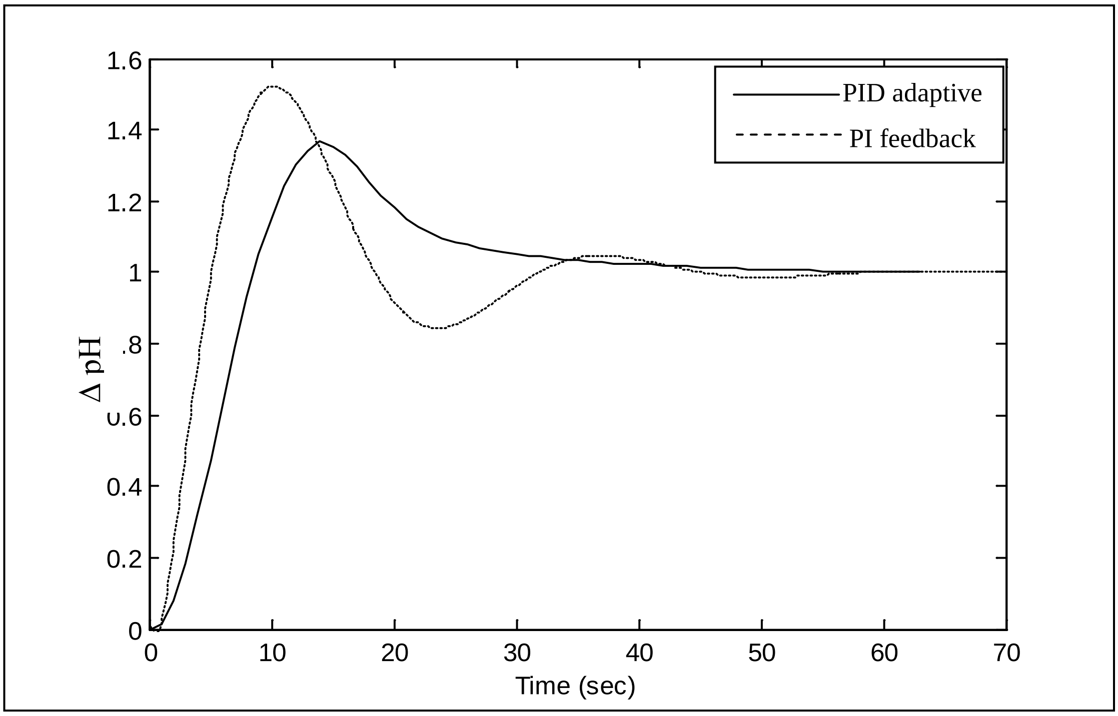

Fig. (7) The comparison between the transient response for PI feedback controller and PID adaptive controller

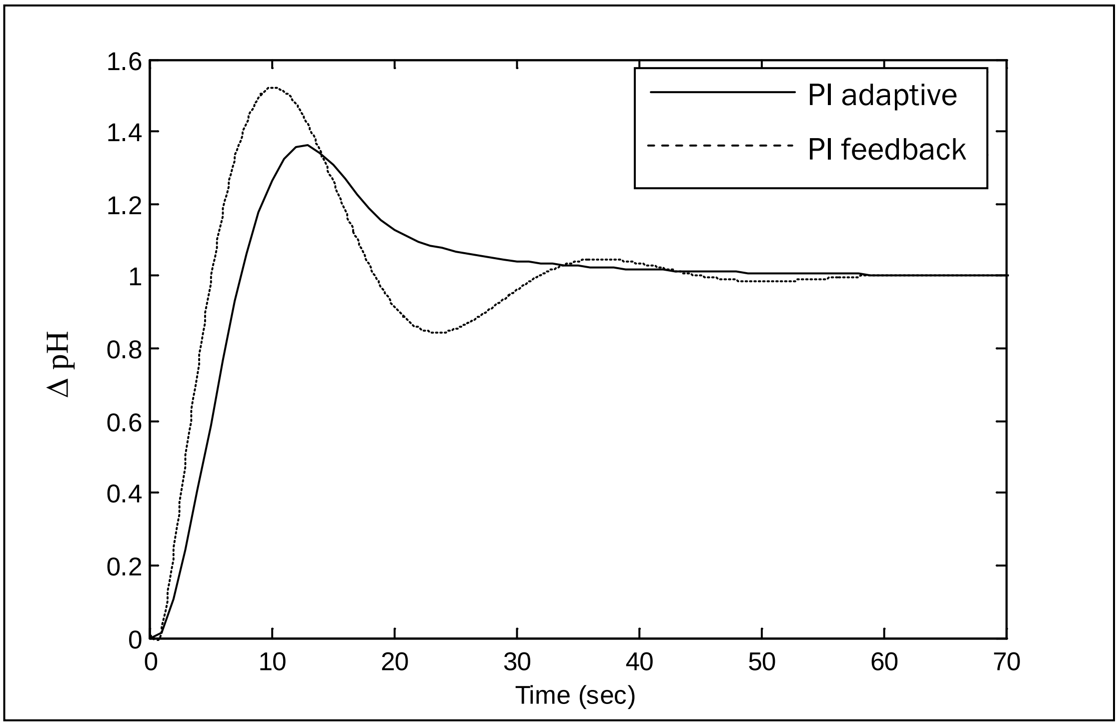

Fig. (8) The comparison between the transient response for PI feedback controller and PI adaptive controller.

السيطرة المتكيفة على عملية التعادل

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الخلاصة

فى هذا العمل تم تطويرنظام سيطره لعملية التعادل فى المفاعل ذي الخلط المستمر (CSTR) حيث ان السلوك الديناميكي و نظام السيطره قد اعنمدا على اساس موازنة الماده.

الموديل الرياضي لعملية التعادل تم وصفه على انه نظام من الدرجه الاولى مع تاخر في الزمن ، دالة التحويل التقريبيه هي:

$$G(s)=\frac{2.95\ e^{-S}}{270\,s+1}$$

تم نحليل استجابة قطب الحامضيه ليعطي دالة تحويل من الدرجه الاولى:

$$G(s)=\frac{1}{0.32\,s+1}$$

تم توصيف متغيرات المسيطر بطريقتين مختلفتين هما **Frequency curve method** و **Process Reaction Curve** لايجاد افضل قيم للمعاملات $\mathbf{K_c}$ و τI و τD . و تم استخدام معيار التكامل **(ITAE)** كاساس للمقارنة بين الطريقتين اعلاه.

استخدم نظام السيطرة المتكيفة كستراتيجية اخرى للمقارنة مع المسيطر التقليدي . وقد وجد بأن المسيطر المتكيف يعطي اداء سيطرة افضل بالمقارنة مع المسيطر التقليدي.

تم استخدام برامج **MATLAB** كاداة في الحل لجميع الحالات المستخدمة في هذا العمل.

الكلمات الدالة: عملية التعادل، السيطرة المتكيفة ، السيطرة التقليديه