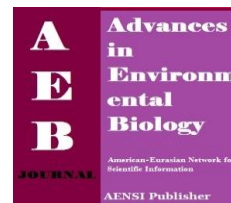




AENSI Journals

## Advances in Environmental Biology

ISSN-1995-0756 EISSN-1998-1066

Journal home page: <http://www.aensiweb.com/aeb.html>

## The Linearity Algorithms for a Surface and PH Process

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### ARTICLE INFO

#### Article history:

Received 20 January 2014

Received in revised form 16

8 April 2014

Accepted 15 August 2014

Available online 28 August 2014

#### Keywords:

Decomposition, Multivariate,  
Interaction, GMC, Heuristic  
Algorithm

### ABSTRACT

This study is intended to maintain liquid surface interaction and PH parameter at the appropriate level. This article purposes QR decomposition algorithm, linearity, and Generic Model control (MMC) and heuristic algorithms for an approximation model of interaction rate and PH process. The comparison of above-said algorithms has been shown. The extracted control rules from the algorithms above are relatively simple and accurate. These algorithms build cyclic system in linear input- output. The simulations have been done by means of PL, PLSPW (weighting of alignment point), Fuzzy Logic Controller (FLC), and Model Predictive Control (MPC). The control efficiency of a heuristic algorithm is more improved with MPC. The derived control rules for heuristic algorithm improve time of settlement ( $T_s$ ) for integral square error.

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**To Cite This Article:** O. Rahmani, A. Taherkhani, M. Rahmani, T. Karimiyan, The linearity algorithms for a surface and PH process. *Adv. Environ. Biol.*, 8(11), 622-630, 2014

## INTRODUCTION

The nonlinear, strongly interacting nature of multivariable chemical processes necessitates the development of solid control methodologies that are capable of coping with both nonlinearities and interactions [3].

In this work for a process with significant nonlinearities, the linear analysis is valid only in an infinitesimally small neighborhood of the operating point. Here three decoupling and linearization state feedback laws are applied to an interacting nonlinear level and pH process. An external linear conventional decentralized PI controller is implemented in the above mentioned level and pH process [1].

Control of pH is important in the chemical industry especially in waste water treatment. However pH processes are difficult to control due to their nonlinear dynamics [2]. In a chemical process involving the mixing of reaching streams (acid, base, salts), the pH is a measure of the hydrogen ion concentration, that determines the acidity / alkaline of a solution [9].

This work is concerned with the comparison of a three linearization algorithms for the synthesis of the nonlinear controller for multivariable interacting nonlinear level and pH process that makes the system linear [4].

The Hirschorn's algorithm is found to be most accurate and efficient as in presented comparison. Decoupling and linearization algorithm and GMC needs some further model refinement but also give acceptable results. The aim of this article is to evaluate the comparison between performance of Hirschorn's algorithm, decoupling and linearization and GMC algorithms based on approximated model as a possible approach to control in real world installations.

In this paper is a brief description of the basics of decoupling and linearization algorithm. Further the available literature is also surveyed in this section. Then deals with the liquid level and pH process. Next describes the basis of Kravaris algorithm. Also describes the basis of GMC algorithm. Then describes the basis of Hirschorn's algorithm. Presents the simulation results with decoupling algorithms along with PI, PI-SPW, FLC, MPC controller such as Kravari's, GMC and Hirschorn's are presented after the application to the model.

## MATERIAL AND METHODS

### General Formulation of the MIMO System:

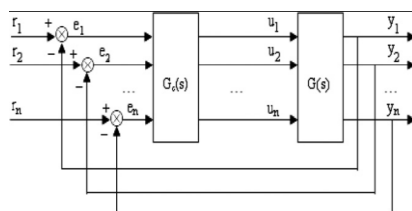
Consider an open loop stable multivariable system with n-inputs and n-outputs as shown in Figure 1. In this process two of the controlled outputs and manipulated inputs are shown in Figure 2. It has the following two control loops. Liquid level and pH coupling with acid flow rate  $u_1$  and base flow rate  $u_2$ . Where  $r_i, i=1, \dots, n$  are

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the reference inputs;  $u_i$ ,  $i=1\dots n$  are the manipulated variables ;  $y_i$ ,  $i=1\dots n$  are the system outputs  $G(s)$  and  $G_c(s)$  are process transfer function matrix and full dimensional controller matrix with compatible dimensions, expressed by

$$G(s) = \begin{bmatrix} g_{11s} & g_{12s} & \dots & g_{1ns} \\ g_{21s} & g_{22s} & \dots & g_{2ns} \\ \dots & \dots & \dots & \dots \\ g_{n1s} & g_{n2s} & \dots & g_{nns} \end{bmatrix} \text{ and}$$

$$G_c(s) = \begin{bmatrix} g_{c11s} & g_{c12s} & \dots & g_{c1ns} \\ g_{c21s} & g_{c22s} & \dots & g_{c2ns} \\ \dots & \dots & \dots & \dots \\ g_{cn1s} & g_{cn2s} & \dots & g_{cnns} \end{bmatrix}$$



**Fig. 1:** Closed loop multivariable control system.

We consider the nonlinear systems with equal number of inputs and outputs of the form

$$\dot{x} = f(x) + \sum_{j=1}^m g_j(x) u_j \quad (1)$$

$$y_i = h_i(x), i = 1, 2, \dots, m \quad (2)$$

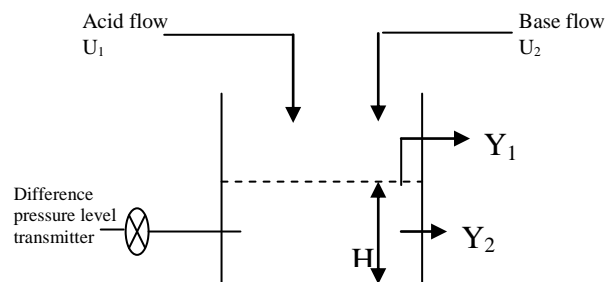
Where

$$u = \begin{bmatrix} u_1 \\ \vdots \\ u_m \end{bmatrix} \in \mathbb{R}^m, \quad y = \begin{bmatrix} y_1 \\ \vdots \\ y_m \end{bmatrix} \in \mathbb{R}^m, \quad x = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} \in \mathbb{R}^n$$

$f(x)$  is a smooth vector field on  $\mathbb{R}^n$ ,  $g_1(x), \dots, g_m(x)$  are smooth vector fields on  $\mathbb{R}^n$ ,  $h_1(x), \dots, h_m(x)$  are smooth scalar fields on  $\mathbb{R}^n$  and  $m < n$ . This is a comparison of linearization algorithms like kravaris decoupling and linearization, GMC, Hirschorn's algorithm.

*Level and pH process:*

A neutralization reaction process, which is schematically shown in Figure 2. A strong acid (HCL) at a concentration of CAO and a strong base (NaOH) at a concentration CBO is also studied [7]. This process is nonlinear and an interaction also exists between the parameters. The aim of this control process is to keep the liquid level and the pH at desired values. It is an established fact that this control problem is challenging when the set point is near the point of neutrality, even if the control system is a SISO. The aim of the control is to keep the liquid level and the pH in the tank at the desired values.  $Y_1$  is a level sensor output and  $Y_2$  is a pH sensor output. As level and pH depends on  $u_1$  (feed flow rate of acid) and  $u_2$  (feed flow rate of base). It is clear, however that an interaction exists in this process.



**Fig. 2:** Schematic Diagram for the level and pH control process. (a)  $u_1$  is the feed flow rate of acid (b)  $u_2$  is the feed flow rate of base (c)  $Y_1$  is the level sensor output (d)  $Y_2$  is the pH sensor output. (e)  $H$  is the height of the liquid.

The process model under the appropriate assumptions is given by

$$\dot{x}_1 = \left( \frac{-k}{s} \right) x_1^{1/2} + \frac{1}{s} (u_1 + u_2) \quad (3)$$

$$\dot{x}_2 = \left[ \frac{-1}{s x_1 \log_{10}(a)} \right] [(b - \text{CAO})U_1 + (b + \text{CBO})U_2] \quad (4)$$

Where  $b = -10^{x_2-14} + 10^{-x_2}$ ,

$$a = 10^{x_2-14} + 10^{-x_2}$$

Output equation is given by

$$y_1 = x_1$$

$$y_2 = x_2$$

Here  $x_1$  and  $x_2$  are the liquid level and the values of pH respectively.  $u_1$  and  $u_2$  are feed flow rate of strong acid and strong base respectively. The tank is a stirred column of 75 cm height and 15.6 cm diameter. A strong acid (HCL) is at a concentration CAO and strong base (NaOH) is at concentration CBO. The aim of this control process is to keep the liquid level and the pH at the desired values. It is known that this control problem is very difficult when the setpoint is nearer to the point of neutrality. The values 's' and 'k' are cross sectional area of the tank  $191\text{cm}^2$  and constant coefficient  $1.8\text{cm}^{5/2}\text{s}^{-1}$  respectively. The feed concentrations are CAO=CBO =  $0.03\text{mol cm}^3$ . The feed rates are constrained as  $0 \leq u_1, u_2 \leq 22\text{cm}^3 \text{s}^{-1}$ .

*Development of Non-Interacting Control Law:*

A non-interacting feedback control law is given by [6]

$$\begin{bmatrix} u_1(x) \\ u_2(x) \end{bmatrix} = \alpha_i(x) + \beta_{ij}(x) \begin{bmatrix} \gamma_1 \\ \gamma_2 \end{bmatrix} \quad (5)$$

( $i = 1, 2; j = 1, 2$ )

where  $\gamma_1(x)$  and  $\gamma_2(x)$  are new inputs.

According to Kravari's decoupling and linearization control theory, control of control law  $u_1$  and  $u_2$  are taken as

$$u_1 = \frac{S(b + \text{CBO})}{(\text{CAO} + \text{CBO})} \left[ \left( \frac{k}{S} \right) x_1^{1/2} - \zeta_{10} x_1 + V_1 \right] + \frac{S x_1 \log_{10}(a)}{(\text{CAO} + \text{CBO})} [-\zeta_{20} x_2 + V_2] \quad (6)$$

$$u_2 = \frac{S(b - \text{CAO})}{(\text{CAO} + \text{CBO})} \left[ -\left( \frac{k}{S} \right) x_1^{1/2} + \zeta_{10} - V_1 \right] + \frac{S x_1 \log_{10}(a)}{(\text{CAO} + \text{CBO})} [\zeta_{20} x_2 - V_2] \quad (7)$$

Substituting  $u_1$  and  $u_2$  in the state model, results in state equation being in decoupled form and linearized form. Before applying this algorithm, liquid level  $Y_1$  depends on  $u_1$  and liquid pH  $Y_2$  depends on  $u_1$  and  $u_2$ . But now it is decoupled and interaction is eliminated.

$$\dot{x}_1 = -\delta_{10} x_1 + v_1$$

$$\dot{x}_2 = -\delta_{20} x_2 + v_2$$

Where  $v_1$  and  $v_2$  are new control inputs.  $x_1$  is liquid level  $x_2$  is liquid pH value.  $\delta_{10} = \delta_{20}$  is constant coefficients.

*Development of GMC Control Law:*

The main objective of GMC is to guide a system from its initial condition to a desired set point by manipulating its input so that the system follows the behavior of a predefined reference model.

A reference model is specified for  $y_1$  and  $y_2$ , according to the GMC formulation. Find a control law, such that  $y$  is equal to  $Y_{sp}$ .

$$\begin{bmatrix} \dot{y}_1 \\ \dot{y}_2 \end{bmatrix} = \begin{bmatrix} K_{11} & 0 \\ 0 & K_{12} \end{bmatrix} \begin{bmatrix} y_{1sp} - y_1 \\ y_{2sp} - y_2 \end{bmatrix} + \int \begin{bmatrix} K_{21} & 0 \\ 0 & K_{22} \end{bmatrix} \begin{bmatrix} y_{1sp} - y_1 \\ y_{2sp} - y_2 \end{bmatrix} dt \quad (8)$$

GMC is mainly used to compensate for model errors and update the model parameters at steady-state as it is very difficult to determine the steady state case. GMC is a multivariable controller with interactions between variables taken into account in the calculation of the values and of the manipulated variables. For a same model GMC algorithm is also included.

According to GMC algorithm control theory, control law  $U_1$  and  $U_2$  taken as

$$u_1 = SV_1 + kx_1^{1/2} - \frac{[Sx_1 \log_{10}(a)V_2 - bSV_1 - bkx_1^{1/2} + CAOSV_1 + CAO kx_1^{1/2}]}{(CAO + CBO)} \quad (9)$$

$$u_2 = \frac{[Sx_1 \log_{10}(a)V_2 - b(SV_1 + kx_1^{1/2}) + CAO(SV_1 + kx_1^{1/2})]}{(CAO + CBO)} \quad (10)$$

Substituting  $u_1$  and  $u_2$  in the state model, results in state equation being in decoupled form and linearized form. Before applying this algorithm, liquid level  $Y_1$  depends on  $u_1$  and liquid pH  $Y_2$  depends on  $u_1$  and  $u_2$ . But now  $x_2$  depends on  $u_1$  and  $u_2$ .

$$\dot{x}_1 = \left( \frac{-k}{S} \right) x_1^{1/2} + \frac{1}{S} \left[ \frac{(SV_1 + kx_1^{1/2})(2CAO + bCAO + CBO)}{CAO + CBO} \right]$$

$$\dot{x}_2 = \frac{1}{CAO + CBO} \left[ \begin{array}{l} b(SV_1 + kx_1^{1/2})(2CAO + CBO + bCAO - b) - \\ CAO(Sx_1 + kx_1^{1/2})[CAO + CBO + b + bCAO] \\ (CBO - b)Sx_1 \log_{10}(a)v_2 + (SV_1 + kx_1^{1/2})(CAO - b) \end{array} \right]$$

So interaction exists even after implementing GMC algorithm in the process.

*Development of Hirschorn's Control Law:*

A derivative function  $h$  along a vector field  $f$  is called a lie derive, denoted by  $L_f h(x) = \frac{\partial}{\partial x} h(x) f(x)$ .

Note that  $\frac{\partial h}{\partial x}$  is a (1,n) row vector and  $f$  (n,1) column vector.

If  $h$  and  $f$  are smooth mapping, the differentiate along the same or another vector field can be repeated, for example the twice repeated lie derivative along  $f$  is written as the function  $L_f(L_f h(x)) = L_f^2 h(x)$ , for  $k \geq 1$ , repeated lie derivative notation is

$$L_f^k h(x) = L_f(L_f^{k-1} h)(x) \quad (11)$$

$$L_f^0 h(x) = h(x) \quad (12)$$

Consider the non-linear system (3 &4), taking the time derivative of the each output component,  $Y_i = h_i(x)$ , the smallest order of each output derivative that explicitly depends on the input  $u$ , as the relative degree  $\zeta_i$ .

$$\dot{y}_i = \frac{dh_i}{dt} = \frac{dh_i}{dx} \frac{dx}{dt} = L_f h_i(x) \quad (13)$$

$$\ddot{y}_i = L_f^2 h_i(x) \quad (14)$$

$$y_i^{(\zeta_i)} = L_f^{\zeta_i} h_i(x) + L_g L_f^{\zeta_i-1} h_i(x) u$$

where  $L_g L_f^{\zeta_i-1} h_i(x) u$  denotes the (1,m) row vector with the  $j^{\text{th}}$  component  $L_{g_j} L_f^{\zeta_i-1} h_i(x)$ . The purpose of the differentiation is to obtain an explicit expression for the control input  $u$ .

In hirschorn's algorithm,  $\zeta^{(k^*)} = m$ ,  $F_1(k) = \text{constant}$ ,  $l=0, \dots, k^*-1$ . Further more, given by  $m \times 1$  matrices  $\beta_{ik}$ ,  $i=0, \dots, m$ ,  $k=0, \dots, r_i-1$  and an  $m \times m$  invertible matrix  $\Gamma$ . The state feedback [7].

$$u = \left[ \Gamma L_g H^{(k^*)}(x) \right]^{-1} \left\{ V - \sum_{i=1}^m \sum_{k=0}^{r_i-1} \beta_{ik} L_f^k h_i(x) - \sum_{l=0}^{k^*-1} \gamma_l [F_1 : I_m - \zeta^{(l)}] E_l L_f H^{(l)}(x) - \Gamma L_f H^{(k^*)}(x) \right\} \quad (15)$$

$$\text{where } H^{(0)}(x) = \begin{bmatrix} L_f^{r_1-1} h_1(x) \\ \vdots \\ L_f^{r_m-1} h_m(x) \end{bmatrix}$$

$$\zeta^{(0)} = \text{Rank}[L_g H^{(0)}(x)] \quad (16)$$

$$k=0, 1, 2, \dots$$

Rearrange the rows of  $L_g H^{(k)}(x)$  so that the first  $\zeta^{(k)}$  rows are linearly independent and denote by  $E_k$ , the corresponding elementary matrix that performs this row rearrangement. Find a  $(m - \zeta^{(k)}) \times \zeta^{(k)}$  matrix  $F_k(x)$  such that  $[F_k(x) : I_{m - \zeta^{(k)}}] E_k L_g H^{(k)}(x) = 0$ . Where  $I_{m - \zeta^{(k)}}$  denotes the  $(m - \zeta^{(k)}) \times (m - \zeta^{(k)})$  identity matrix, define

$$H^{(k+1)}(x) = \begin{bmatrix} \text{first } \zeta^{(k)} \text{ rows of } E_k H^{(k)}(x) \\ [F_k : I_{m - \zeta^{(k)}}] E_k H^{(k)}(x) \end{bmatrix} \quad (17)$$

$$\zeta^{(k+1)} = \text{Rank}[L_g H^{(k+1)}(x)] \quad (18)$$

following the steps of the algorithm, a sequence of non negative integers  $0 \leq \zeta^{(0)} \leq \zeta^{(1)} \leq \zeta^{(2)} \leq \dots \leq \zeta^{(k)} \leq \dots \leq m$ . Thus there is a least positive integer  $k^*$  such that  $\zeta^{(k^*)}$  is maximal. In other words, the algorithm will always terminate after a finite number of steps equal to  $k^*$ , and at the last step, one will either have  $\zeta^{(k^*)} = m$ .

The Hirschorn's control algorithm based on non-linear feedback transformation is applied to a non-linear interactive level and pH process.

$$u_1 = \frac{S}{(CAO + CBO)} [bV_1 - b\zeta_{10}x_1 + b\frac{k}{s}x_1^{1/2} - \frac{bk^2}{2S^2} + CBOV_1 - CBO\zeta_{10}x_1 + CBO\frac{k}{s}x_1^{1/2} - CBO\frac{k^2}{2S^2} + x_1 \log_{10}(a)V_2 - x_1 \log_{10}(a)\zeta_{20}x_2] \quad (19)$$

$$u_2 = \frac{S}{(CBO + CAO)} [-bV_1 + b\zeta_{10}x_1 - b\frac{k}{s}x_1^{1/2} + \frac{bk^2}{2S^2} + CBOV_1 - CAO\zeta_{10}x_1 + CAO\frac{k}{s}x_1^{1/2} - CAO\frac{k^2}{2S^2} - x_1 \log_{10}(a)V_2 + x_1 \log_{10}(a)\zeta_{20}x_2] \quad (20)$$

Substituting  $u_1$  and  $u_2$  in the state model, results in state equation being in decoupled form and linearized form. Before applying this algorithm, liquid level  $Y_1$  depends on  $u_1$  and liquid pH  $Y_2$  depends on  $u_1$  and  $u_2$ . But now it is decoupled and interaction is eliminated.

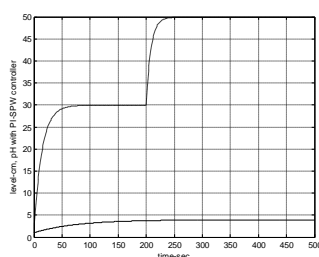
$$\dot{x}_1 = v_1 - \delta_{10}x_1 - \frac{k^2}{2S^2}$$

$$\dot{x}_2 = v_2 - \delta_{20}x_2$$

Where  $v_1$  and  $v_2$  are new control inputs.  $x_1$  is liquid level  $x_2$  is liquid pH.  $\delta_{10} = \delta_{20}$  is constant coefficients.

### 3. Results:

At first, PI controller is added for level and pH process along with the decoupling kravaris algorithm. It is reproduced in Figure 3. It shows that the output response of the level and pH when the set point of the level is changed from 1 to 30cm and pH from 1 to 4. The sudden disturbance introduced at time of 200 sec in level is not affecting the pH process.



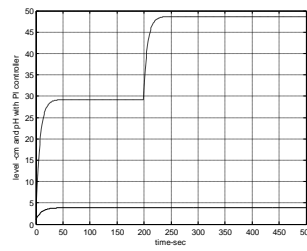
**Fig. 3:** Process with decoupling ( kravaris) with PI controller for level and pH process.

Next PI-SPW controller is added along with the decoupling kravaris algorithm. It is reproduced in Figure 4. The sudden disturbance introduced at time of 200 sec in level is not affecting the pH process. It can be seen from the figure that the influence of the control performance is improved compared to Figure 3.

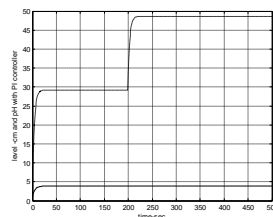
Then FLC controller is added along with the decoupling kravaris algorithm. It is reproduced in Figure 5. The sudden disturbance introduced at time of 200 sec in level is not affecting the pH process. It can be seen from the figure that the influence of the control performance improved when compared to Figure 4.

Next applying GMC algorithm with external PI controller is shown in Figure 6. It shows the output response of the level and pH when the set point of the level is raised from 1 to 30cm and pH from 1 to 4. The

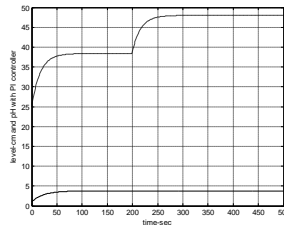
sudden disturbance introduced at time of 200sec in level is not affecting the pH process. It can be seen from the figure that under the influence of the controller performance, ISE is improved.



**Fig. 4:** Process with decoupling (kravaris) with PI-SPW controller for level and pH process.

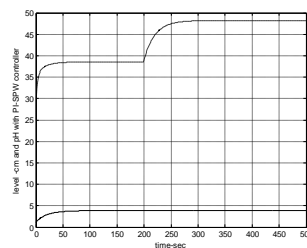


**Fig. 5:** Process with decoupling ( kravaris) with FLC controller for level and pH process.



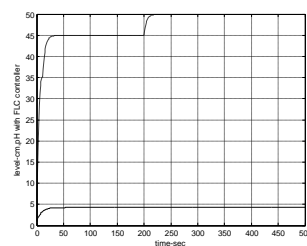
**Fig. 6:** Process with decoupling ( GMC) with PI controller for level and pH process.

Next GMC algorithm with external PI set point weighting controller is shown in Figure 7. The sudden disturbance introduced at time of 200sec in level does not affect the pH process. It can be seen from the figure that the ISE is improved than Figure 6.



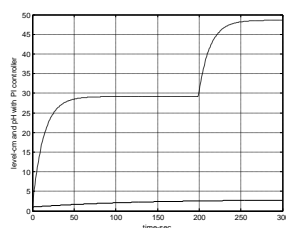
**Fig. 7:** Process with decoupling (GMC) with PI-SPW controller for level and pH process.

Then decoupling and linearization with external Fuzzy logic controller is added as shown in Figure 8. The sudden disturbance introduced at time of 200sec in level was not affecting the pH process. It can be seen from the figure that the influence of the control performance improved where compared to Figure 7.



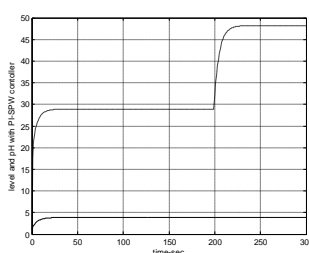
**Fig. 8:** Process with decoupling (GMC) with FLC controller for level and pH process.

Level pH control experiment with PI controller is carried out with the Hirchorn's algorithm. The result is shown in Figure 9 [8]. It shows the output response of the level and temperature when the set point of the level is changed from 1 to 30cm and pH from 1 to 4. The sudden disturbance introduced at time of 200sec in level is not affecting the temperature process. It can be seen from the figure that under the influence of the controller performance, ISE is also improved



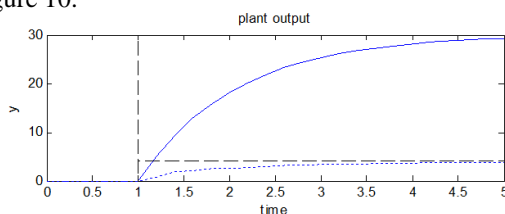
**Fig. 9:** Process with decoupling (Hirchorn's) with PI controller for level and pH process.

Next level and pH control experiment with PI-SPW controller is carried out with the Hirchorn's algorithm. The output response is shown in Figure 10. It can be seen from the figure that the control performance is improved when compared to Figure 9.



**Fig. 10:** Process with decoupling (Hirchorn's) with PI-SPW controller for level and pH process.

Then the level and pH control experiment with MPC controller is carried out with the Hirchorn's algorithm. The corresponding output is shown in Figure 11. It can be seen from the figure that the control performance is improved when compared to Figure 10.



**Fig. 11:** Process with decoupling (Hirchorn's) with MPC controller for level and pH process.

#### 4. Discussions:

**Table 1:** Comparison of controller performance (Kravaris algorithm).

	Process	Ts(sec)	ISE
PI	Level	80	1.096e+004
	pH	80	165.58
PI-SPW	Level	50	5.935e+004
	pH	50	142.197
FLC	Level	30	3.338e+003
	pH	40	49.5

Table 1 shows the performance of Level pH process with controllers. It is inferred that FLC controller gives less Settling time (Ts) and Integral Square Error (ISE) for both the process to reach the desired set point.

**Table 2:** Comparison of controller performance (GMC algorithm).

	Process	Ts(sec)	ISE
PI	Level	80	Interaction exists
	pH	80	Interaction exists
PI-SPW	Level	50	Interaction exists
	pH	50	Interaction exists
FLC	Level	30	Interaction exists
	pH	30	Interaction exists

GMC is not suitable for the Level pH process. Interaction exists even after implementing GMC algorithm in the process.

**Table 3:** Comparison of controller performance (Hirchorn's algorithm).

Hirchorn's		Ts (sec)	ISE
PI	level	50	6.419e+003
	pH	50	585.07
PI-SPW	level	25	1.352e+003
	pH	25	30.79
MPC	level	3	25
	pH	4	25

Table 3 shows the performance of Level pH process with controllers. It is inferred that MPC controller gives less Settling time (Ts) and Integral Square Error (ISE) for both the process to reach the desired set point.

This work concerns the comparison of control laws of a linearization algorithms for the synthesis of controllers for multivariable nonlinear processes that makes the level and pH system linear. Hirchorn's linearization feedback algorithm is most accurate and efficient in the comparison. Decoupling and linearization feedback control law and GMC needs further model simulation. They too give acceptable results. This paper reports the simulation application of the Hirchorn's control law, Decoupling and linearization feedback control law and GMC control law to the chemical process, (level and pH control process). Results of these simulations are presented in Table 1. This includes that Hirschorn's algorithm with PI controller gives less Settling time and Integral Square Error for both level and pH parameter.

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