Iterative Learning Control Design for a Non-Linear Multivariable System

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Abstract: Multivariable systems referring to the relationships between input variables and output variables, exhibit complex dynamics. This paper presents an access to model an auto-tuned PI controller to control a class of multivariable systems using ideal decoupler and Iterative Learning Controller techniques. The MIMO system is converted into two SISO systems using the decoupler. Iterative Learning Control offers a good scheme for high-precision positioning control and fast process response. In the quadruple tank system controlling flow ratios operates the structure in minimum and non-minimum phase system. The performance will be cause if the system moves from the minimum to the non-minimum phase arrangement, and vice versa. The performance of the proposed system is analyzed using simulation for source tracking and interruption elimination behaviour. Simulation results affirm the efficacy of the suggested control approach.

Keywords: Multi input Multi output system, PI Controller, Iterative Learning Control, Minimum and non-minimum phase system, Quadruple tank system.

1. INTRODUCTION

Industrial processes are largely nonlinear and multivariable systems. Complicated interactions always occur between the measurement signals and the control signals. Owing to the relationships of several variables for input and output. A suitable controller for MIMO systems is difficult to design. Several control techniques available to handle multivariable systems.

(Johansson et al., 2000) had first introduced the Quadruple Tank System (QTS). Since its beginning, QTS is a very well-known standard for measuring advanced control approaches for multivariable control because, depending on its shape and operating points, it has both minimum and non-minimum phase functional points. It has an adjustable zero transmission whose position differs from half left to right half of s-plane.

This paper proposes a design concept using decoupling and ILC techniques for auto tuned decentralised PI controllers to settle the issue of interaction in quadruple tank systems, which is a multivariable benchmark model used in the literature. One essential problem in manipulating a quadruple tank system is how to handle the interactions between two loops. A successful approach is the implementation of the so-called decentralized control strategy: each loop is independently controlled by one controller, based on local strategies and performance says (Angeline et al., 2013).

Sensors and final control element are used in the Multivariable processes with higher order dynamics. Higher order system were minimised to first order plus delay time for decentralized control design discussed in (Nagarajapandian et al., 2019). The entire system of the natural world would not be an exact model of integer order. In earlier times, due to lack of system availability, all the real universe processes are approached into a numeral order process proposed by (Febina et al., 2020). But now, new computational techniques have been used to transform approximate whole order systems into specific fractional order processes. (K.Yamada, 2005) discussed that all appropriate stabilising controllers for direct minimum phase condition should parameterize the method of designing revised PID control for minimum phase condition. With a minimum and non-minimum phase behaviour resulting from the multivariable nature of the difficult, the necessary controller structure is used. The quadruple tank with various PID controller structures was used for this purpose and the output of the control techniques was evaluated.

One of the major experiments for investigators in the area of control systems has been effective control of this quadruple tank process model. This process has implemented and tested several control methods, mid which we find: Decentralized Proportional Integral (PI) Control, (K. J. Astrom et al., 2002; A.Numsomran et al., 2004), Nonlinear Model Predictive Control (T. Raff et al., 2006), Model Predictive Control Based on Quadratic Cost Function (D. M. Delapena et al., 2006), Neural Model Predictive Control (N. Sivakumaran et al., 2006), Quantitative Feedback Method (S. M. Alavi et al., 2006), the Robust Performance Number (RPN) method to qualify the IO-controllability of the system (J. O. Trierweiler et al., 2002) and so on. Most of the control methods recently proposed follow a good decoupling control scheme. In these control schemes Iterative Learning control can be used in the control design stage more by system if an effective model of the system is used.

As a mechanism for reliable reference monitoring of repeated procedures, Iterative Learning Control (ILC) was first suggested. Nowadays, ILC is known as a modern, intelligent monitoring system, which is quite influential between controller engineers. The popularity of iterative learning control stems from the fact that closed-loop control systems do the same for each subsequent approach.

The challenge of iterative learning control considers that the function of training is to implement a similar monitoring order multiple times. The system is reverted to the same primary condition which is on the favourite trajectory between each command use. The approach used here assumes that there is a feedback controller, and the learning law simply adjust the control from one iteration to the next to the feedback controller to minimize tracking error as proposed by (Longman RW, 2000).

(Owens DH, 2016) reports on control signals in the form of functions or period series which can be assumed to be vector space elements. The approach is based on mathematical models of Iterative Learning Control that use operator-dependent representations. This choice of approach enhances the simplicity of the presentation but due attention needs to be given to analysing the equations. Formal concepts of the control algorithm design problem are used throughout.

Another and elective admittance to tuning a Smith indicator is created by the technique of Repetitive Control (RC) (Kok Kiong Tan et al., 2009). In view of gaining from past redundancies, RC can expand gadget execution in resulting reiterations and to create a certified and advanced arrangement of regulator signs to follow a rehashed source signal. The fundamental idea related with this article is to utilize ILC as a technique to deliver the ultimate regulator signal for measures that are basic in persistently checking a set point. On account of common ILC applications for mechanical technology and movement frameworks where there is brief period delay, this reference grouping can be the ordinary dull sign for the control framework to perform monotonous activities. For process control applications, the reference frequency and the repeated iteration can be determined to be at an ultimate frequency. Via a feedback closed loop on relays, this frequency can be generated effectively. By summing a time-delay and feedback path, the essential structure is changed with the end goal that the ILC strategy is pertinent to long-dead cycles. When the learning cycle has met, the PI regulator must have accessible a scope of ideal control signals for auto-decoupling tuning.

The proposed work of this paper is to design a controller for the multi input and multi output cycle in both minimum and non-minimum phase conditions where it is built in three steps in the control systems. Initially decoupler is built to divide the MIMO scheme into two input and two output regulator loops; then a Relative Gain Array (RGA) model is configured with a decentralized control structure. Finally, Iterative learning controller tunes the best PI controller parameters with the assistance of L and Q filter design, and compares the results.

2. PROCESS DESCRIPTION AND MODELLING

In chemical engineering laboratories, a quadruple tank device suggested in (Johansson et al., 2000) was used to demonstrate the performance limitations of multivariable systems due to un conditioning of the right half of the plane. Four associated tanks and their two pumps form the QTS. For QTS schematics are described in the Fig. 1. u_1 and u_2 (input voltages to the pumps) are the process inputs, and y_1 and y_2 are the outputs (voltages from measuring devices). The goal is to control the level of the inlet-flow of the lower two tanks. The output of each pump is divide into two by a 3-way valve. So the output of each pump goes into two tanks, one lower and one upper, diagonally opposite, and the position of the valve controls the split-up ratio. The scheme can be properly controlled, either in the minimum phase or in the non-minimum phase, with the position of the two valves being changed.

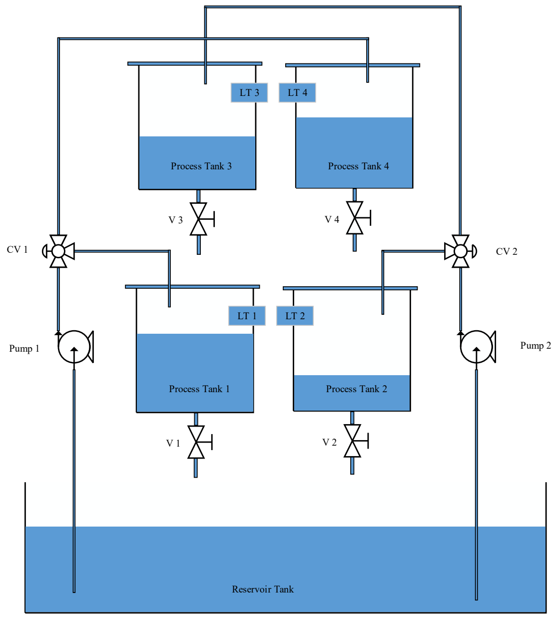

Fig. 1. Simplified layout of Quadruple Tank System.

Let the γ constraint be calculated on the basis of how to configure the valves. If γ_1 is the flow to the first tank ratio, then the flow to the fourth tank would be $(1 - \gamma_1)$. Correspondingly, if γ_2 is the proportion of the movement to the second tank, the movement to the third tank would be $(1 - \gamma_2)$. V_i is the voltage applied to Pump 'i' and K_iV_i is the corresponding flow rate. The constraints γ_1 γ_2 [0, 1] are calculated by the positioning of the valves before the experiment. The movement to tank 1 is $\gamma_1 K_1V_1$ and the movement to tank 4 is $(1- \gamma_1) K_1V_1$, and to tank 2 and tank 3, accordingly. The constant of gravity is marked as 'g'. The level signals measured are $y_1= k_ch_1$ and $y_2= k_ch_2$. Equation (1) to (4) represents the quadruple tank system non-linear state equation.

$$\frac{dh_1}{dt} = -\frac{a_1}{A_1}\sqrt{2gh_1} + \frac{a_3}{A_1}\sqrt{2gh_3} + \frac{\gamma_1 k_c}{A_1}v_1 \tag{1}$$

$$\frac{dh_2}{dt} = -\frac{a_2}{A_2}\sqrt{2gh_2} + \frac{a_4}{A_2}\sqrt{2gh_4} + \frac{\gamma_2 k_c}{A_2}v_2 \tag{2}$$

$$\frac{dh_3}{dt} = -\frac{a_3}{A_3}\sqrt{2gh_3} + \frac{(1-\gamma_2)k_c}{A_3}v_2 \tag{3}$$

$$\frac{dh_4}{dt} = -\frac{a_4}{A_4}\sqrt{2gh_4} + \frac{(1-\gamma_1)k_c}{A_4}v_1 \tag{4}$$

Where

A_i is the Tank 'i' cross-sectional area
a_i is the cross section of the Tank 'i' outlet hole
h_i, the water flat in the 'i' tank

The four tank (h_i) levels are known as the state variables (x_i), and the voltages supplied to the pumps (v_1 and v_2) respectively. Tank 1 and tank 2 levels are the input variables (u_i) and the output variables (y_i).To linearize the non-linear system, $x_i = h_i - h_i^0$ and $u_i = v_i - v_i^0$ where h_i^0 and v_i^0 are the steady state values of h_i and v_i correspondingly. Using the expansion of the Taylor series defined in Equation (5), the linearized state space model is obtained with the system matrix and the model appears in Equations (6) and (7).

$$\dot{x}=\dot{h}_i = f(h_i^0, v_i^0) + \left.\frac{\partial f(h,v)}{\partial h^T}\right|_{h_i=h_i^0} (h_i - h_i^0) + \left.\frac{\partial f(h,v)}{\partial v^T}\right|_{v_i=v_i^0} (v_i - v_i^0) \tag{5}$$

in which $f(h_i^0, v_i^0) \xrightarrow{yields} 0$; $\left.\frac{\partial f(h,v)}{\partial h^T}\right|_{h_i=h_i^0} \xrightarrow{yields} A$;

$\left.\frac{\partial f(h,v)}{\partial h^T}\right|_{h_i=h_i^0} \xrightarrow{yields} X$; $\left.\frac{\partial f(h,v)}{\partial v^T}\right|_{v_i=v_i^0} \xrightarrow{yields} B$;

and $(v_i - v_i^0) \xrightarrow{yields} U$.

The linearity state model can be written as

$$\dot{X} = AX + BU \tag{6}$$

$$Y = CX + DU \tag{7}$$

Where,

A= System matrix

B= Input matrix

C= Output matrix

D= Transmission matrix

$$A = \begin{bmatrix} -\frac{1}{T_1} & 0 & \frac{A_3}{A_1 T_3} & 0 \\ 0 & -\frac{1}{T_2} & 0 & \frac{A_4}{A_2 T_4} \\ 0 & 0 & -\frac{1}{T_3} & 0 \\ 0 & 0 & 0 & -\frac{1}{T_4} \end{bmatrix} \tag{8}$$

$$B = \begin{bmatrix} \frac{\gamma_1 k_1}{A_1} & 0 \\ 0 & \frac{\gamma_2 k_2}{A_2} \\ 0 & \frac{(1-\gamma_2)k_2}{A_3} \\ \frac{(1-\gamma_1)k_1}{A_4} & 0 \end{bmatrix} \tag{9}$$

$$C = \begin{bmatrix} k_c & 0 & 0 & 0 \\ 0 & k_c & 0 & 0 \end{bmatrix} \tag{10}$$

$$D = 0; \tag{11}$$

State vector, $X = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$; Input Vector, $U = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$

Output vector, $Y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}$

The time constants are determined by Equation (12).

$$T_j = \frac{A_j}{a_j}\sqrt{\frac{2h_j^0}{g}}, \text{ where } j = 1,\ldots,4 \tag{12}$$

The specification standards and the process's stable state functional points are expected as per the system given in the (Johansson, 2000) and are represented individually in Table 1 and Table 2.

Table 1. Process specification.

Area for T_1 and T_2 (A1,A3)	28 cm^2
Area for T_2 and T_4 (A2,A4)	32 cm^2
a1,a3	0.071 cm^2
a2,a4	0.057 cm^2
K_c	0.5 cm^2

Table 2. Operational points of the system.

Stable state specification	Minimum Phase	NonMinimum Phase
$h_1^0, h_2^0 [cm]$	(12.4,12.7)	(12.6,13)
$h_3^0, h_4^0 [cm]$	(1.8,1.4)	(4.8,4.9)
$v_1^0, v_2^0 [V]$	(3.00,3.00)	(3.15,3.15)
$k_1, k_2 [cm^3/V_s]$	(3.33,3.35)	(3.14,3.29)
γ_1, γ_2	(0.70,0.60)	(0.43,0.34)

Matrices A, B, and C are computed with these values in the equations (8) to (11). Transfer function matrices are attained by MATLAB environment and are given for operating points of minimum phase and non-minimum phase condition is expressed in (13) and (14), accordingly.

$$G_-(s) = \begin{bmatrix} \frac{2.6}{1+62s} & \frac{1.5}{(1+23s)(1+62s)} \\ \frac{1.4}{(1+30s)(1+90s)} & \frac{2.5}{1+90s} \end{bmatrix} \tag{13}$$

$$G_+(s) = \begin{bmatrix} \frac{1.5}{1+63s} & \frac{2.5}{(1+39s)(1+63s)} \\ \frac{1.4}{(1+56s)(1+91s)} & \frac{1.6}{1+91s} \end{bmatrix} \tag{14}$$

In the transfer matrix G, there are two zeros, one of which is permanently in the left half of the s-plane, however, depending on the position of the 3-way valve, the other can be in either the left half or the right half of the s-plane. The structure is in the minimum phase, if the γ_1 and γ_2 standards satisfy condition

$0 < \gamma_1 + \gamma_2 < 1$ and if the γ_1 and γ_2 values satisfy condition $1 < \gamma_1 + \gamma_2 < 2$ and are in the non-minimum phase.

3. CONTROLLER DESIGN

3.1 Decoupler Design

A common approach for dealing with control loop interactions is implementing control schemes that are non-interactive or decoupling. The intention of this regulator is to remove the properties of interactions with the round entirely. It is achieved by defining the compensation scheme identified as the "decoupler" The aim of the decoupler is to dissolve a multivariable method toward different autonomous sub-systems of single loops. When designing such a controller, whole or perfect decoupling occurs, and the multivariable procedure can be regulated by self-determining loop controllers proposed in (P. Nordfeldt et al., 2006). Fig. 2. Shows the general control structure for the decoupling.

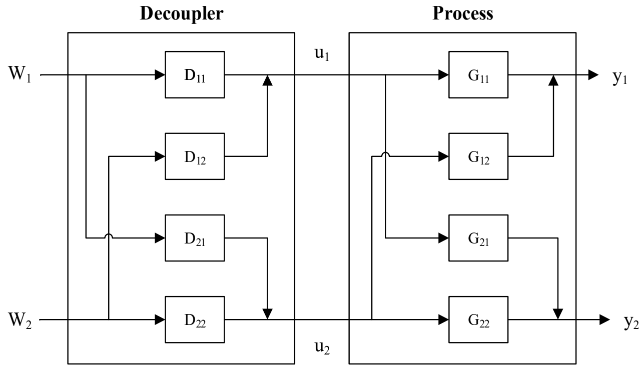

Fig. 2. Control structure for the decoupler.

The ideal decoupler is chosen because the decoupling elements are independent of the controllers of the forward direction, so no redesign of the decoupler elements is necessary for the controllers to be tuned on line. Additionally, since decoupling happens among the frontward path regulator signs and the system heights and not amid the reference points and the outputs, this technique can solve both servo and regulator problems proposed by (Angeline Vijula et al., 2014).The ideal decoupler is constructed as indicated in Equation (15).

$$D(s) = \begin{bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{bmatrix} \tag{15}$$

Where the diagonal element, $D_{11} = D_{22} = 1$(for ultimate decoupler) and off crosswise elements, $D_{12} = -\frac{G_{12}D_{22}}{G_{11}}$ and $D_{21} = -\frac{G_{21}D_{11}}{G_{22}}$. In Equations (16) and (17) respectively, decoupler matrices designed for minimum and non-minimum phase systems are given.

$$D_{-}(s) = \begin{bmatrix} 1 & \frac{-0.577}{(1+23s)} \\ \frac{-0.5}{1+30s} & 1 \end{bmatrix} \tag{16}$$

$$D_{+}(s) = \begin{bmatrix} 1 & \frac{-1.667}{(1+39s)} \\ \frac{-1.5625}{1+56s} & 1 \end{bmatrix} \tag{17}$$

3.2 Relative Gain Array

Selecting the correct input-output pairing is needed to design the control system for MIMO systems with interactions. To identify suitable combination, it is important to determine the degree of interface among variables. For both minimum and non-minimum phase conditions, to compare the combination of inputs-outputs, Relative Gain Array (RGA) analysis is used. RGA is given by equation (18).

$$\Lambda = \begin{bmatrix} \lambda_{11} & \lambda_{12} \\ \lambda_{21} & \lambda_{22} \end{bmatrix} \tag{18}$$

λ_{11} is obtained as 0.63 for the minimum phase system, dropping in the range of $0.5 < \lambda_{11} < 1$, the combination is therefore calculated as y_1-u_1 and y_2-u_2. However, λ_{11} is acquired as 0.375 for the non-minimum phase system, which lies in the range of $0 < \lambda_{11} < 0.5$, so the appropriate combination is initiate as y_1-u_2 and y_2-u_1.

3.3 Basic PI controller

A controller with PI consists of a basic controller with two names. The letters are P and I represent respectively proportional, integral. To evoke a desired response, the characteristics of each term are used. Equations (19) and (20) demonstrate the expressions of the Propositional and Propositional Integral controllers, respectively. The P control exploit or signal is proportionate to the error signal, and the control signal is displayed accordingly by (E.Govinda Kumar et al., 2014).

$$u(t) = K_p e(t) \tag{19}$$

As follows, the PI control action or sign is given as,

$$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int e(t)dt \right) \tag{20}$$

Where K_p is proportional gain or constant and T_i integral time constant.

3.4 Iterative Learning controller

Iterative Learning Controller may be used for processes involving repeated execution of the same direction. The error signal is used for the next run to adjust the tuning controls. A number of conditions must be satisfied for ILC to be efficient.

1. A plant performs time after time for a certain process that ends at a set point, $\tau_P > 0$
2. Dynamics for model are not time-depends
3. The expected response $y_e(t)(t \in [0, \tau_p])$
4. The initial states are the same for each trial

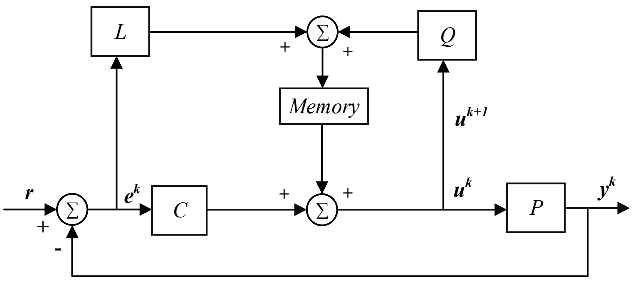

Fig. 3. ILC Configuration structure with feedback.

Fig. 3. Shows the k^th test control signal, u^k is deposited in a memorial buffer. The e^k tracking error is filtered during the runtime of the plant and used to create the u^{k+1} steering signal. The L-filter is based on a model of a plant. Conversely this model is not ever correct. This suggests that the L-filter can lead to a high frequency control belt being unstable in testing. In order to address this problem, it is planned to implement a low pass Q-filter in the memorial loop. The Q-filter is calculated to reduce frequency modules in the system model and also Q-filter can either be placed in front or in the memorial component in the Feedback round. It is generalized and gives more space to choose the filter L and Q.

3.4.1 Calculation of L & Q filter

By via the structure of fig.3, the law of knowledge will be

$$u_{k+1} = Qu_k + Le_k + Ce_{k+1} \tag{21}$$

The equation (21) can be rewritten as,

$$u_{k+1} = Qu_k + Le_k + Cr - Cy_{k+1,} \quad \text{with: } e_{k+1} = r - y_{k+1}$$

$$u_{k+1} = Qu_k + Le_k + Cr - CPu_{k+1}$$

$$(1+CP)u_{k+1} = Lr - Lu_kP + Qu_k + Cr$$

$$(1+CP)u_{k+1} = (Q-LP)u_k + r(C+L)$$

$$u_{k+1} = (1+CP)^{-1}(Q-LP)u_k + r(1+CP)^{-1}(C+L) \tag{22}$$

It is sufficient to satisfy the following requirement for conver gence of the learning law,

$$\left|u_{k+2} - u_{k+1}\right| \le \rho\left|u_{k+1} - u_k\right|, \text{ With } \rho < 1 \tag{23}$$

To choose Quick Convergence

$$(1+CP)^{-1}(Q-LP) << 1 \tag{24}$$

It's agreed that Q filter and L filter that satisfies the condition, (Q-LP) = 0 will offer convergence theoretically after one trial. The L-filter must be chosen as,

$$L = QP^{-1} \tag{25}$$

Conjunction is not the only ILC criterion. robustness also will increase. The transformation from r to y is,

$$\frac{y}{r} = \frac{(1-Q)^{-1}(L+C)P}{1+(1-Q)^{-1}(L+C)P} = \frac{(L+C)P}{(1-Q)+(L+C)P} \tag{26}$$

Earlier the L filter have picked, $L = QP^{-1}$ In equation (26) reduces to,

$$\frac{y}{r} = \frac{Q+CP}{1+CP} \tag{27}$$

For a correct response Q must also be selected as belows,

$$Q(s) = \begin{cases} 1, \forall\, \omega \in [0, \omega_c] \\ 0, \forall\, \omega > \omega_c \end{cases} \tag{28}$$

3.4.1 Design of the approximate controller of ILC

If the ILC's L and Q filter is well chosen the learning rule wil l converge, that does mean

$$\begin{aligned} \lim_{k\to\infty} u_{k+1} &= \lim_{k\to\infty} u_k = \bar{u} \\ \lim_{k\to\infty} e_{k+1} &= \lim_{k\to\infty} e_k = \bar{e} \end{aligned} \tag{29}$$

With the above specified convergence situation,
the learning rule can be rewritten as,

$$\bar{u} = Q\bar{u} + L\bar{e} + C\bar{e}$$

$$(1-Q)\bar{u} = (L+C)\bar{e}$$

$$\bar{e} = (1-Q)^{-1}(L+C)\bar{e} \tag{30}$$

The part $(1-Q)^{-1}(L+C)$ can be seen as a latest Feedback controller of the ILC.

3.4.2 Parameter values of L and Q filter for QTS

Let us consider the Plant model for both operating points like minimum and non- minimum phase systems with their respective Q and L filter value as listed in Table 3. With a help of equation (25), from plant transfer function in equation (13) and (14), it is considered that G_{-11} and G_{-22} for minimum phase system and also G_{+11} and G_{+22} for non-minimum phase system for designing a Q and L filter. It will consider the tank 1 and tank 2 transfer function for designing their Q and L filter because it will control only the level of that particular tanks,the cutoff filter's frequency ω_c must be selected in such a waythat the ILC becomes resilient. How to select ω_c, where the uncer tainty of the plant model begins, is not clear.The option of ω_c is a trade-off among stability (low ω_c) and efficiency (high ω_c) in practice. The following is the explanation for the second order of the Q-filter. The L-filter consists of the plant's inverse component (QP^{-1}).To make the L-filter proper, P^{-1} has a zero-pole surplus of 2, so Q would have a pole-zero surplus of 2.ω_c is selected from the plant transfer function bode diagram and it is shown in Fig. 4.

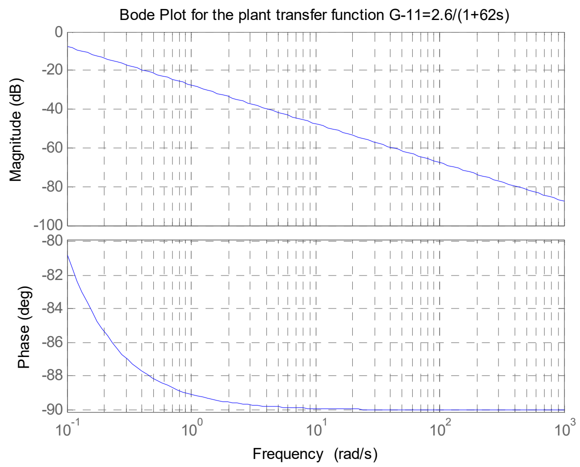

Fig. 4. Bode Diagram of Plant (G_{-11}) transfer function.

Table 3. Q and L-filter values of plant transfer function.

Plant Transfer function	Q filter	L filter
$G_{-11}=\dfrac{2.6}{1+62s}$	$Q=\dfrac{0.0044}{s^2+0.132s+0.0044}$	$L=\dfrac{2.728s+0.044}{2.6s^2+0.343s+0.0114}$
$G_{-22}=\dfrac{2.5}{1+90s}$	$Q=\dfrac{0.0021}{s^2+0.090s+0.0021}$	$L=\dfrac{0.189s+0.0021}{2.8s^2+0.252s+0.0058}$
$G_{+11}=\dfrac{1.5}{1+63s}$	$Q=\dfrac{0.0012}{s^2+0.069s+0.0012}$	$L=\dfrac{0.0756s+0.0012}{1.5s^2+0.103s+0.0018}$
$G_{+22}=\dfrac{1.6}{1+91s}$	$Q=\dfrac{0.00057}{s^2+0.048s+0.00057}$	$L=\dfrac{0.0524s+0.00057}{1.6s^2+0.0768s+0.0009}$

4. RESULT AND DISCUSSIONS

Fig. 5. Indicates the response of QTS controlled variables for set point tracking in the minimum phase without decoupler. Tuning of the parameters of the Propositional with Integral controller will offer the process under study with adequate closed-loop output in terms of robustness, overshoot setting time and error value, etc. Fig. 5. Second graph shows the response of PI controller output with that particular time variations with the maximum voltage was 5 Volts. Delay times are negligible for those process systems. Level 3 and level 4 describes the disturbance of tank 1 and tank 2, taking level parameters for tank 3 and tank 4 as 1 cm and 0.5 cm.

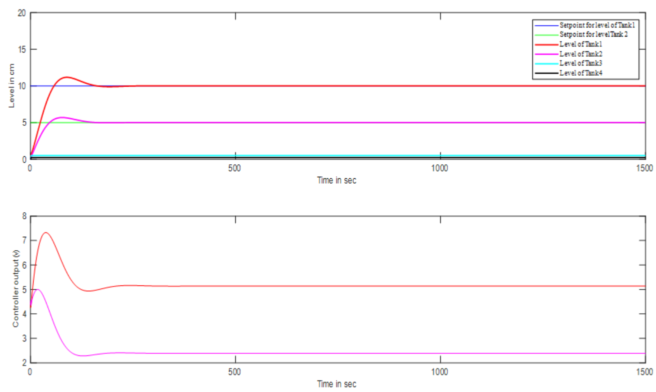

Fig. 5. Response of PI controller without Decoupler under minimum phase condition.

Fig. 6, the non-minimum phase without decoupler for set point tracking, the response of controlled QTS variables is seen. In fig. 6. First graph response shows the settling time and error value was increased due to the non-minimum phase system compare to minimum phase systems without decoupler for interactions between the tank 1 and tank 2. It is observed that when operated in non-minimum phase condition the process produces inverse response. In this operating condition, simple PI controller does not provide better control of the process.

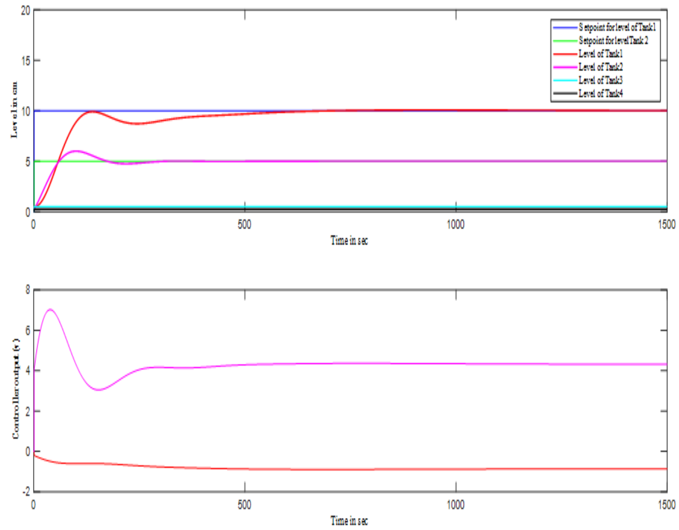

Fig. 6. Responses of PI controller without Decoupler under non-minimum phase condition.

More setting time and large error will be produced in this case for the PI controller. This issue addressed by using PI control with decoupler. Fig.7.displays the response of QTS controlled variables in the minimum phase with the fixed point tracking decoupler. It is obviously exposed that the response is complimentary from interactions. With the assistance of decoupler with PI controller, settling time was reduced as well as error value also reduced. But rise time will be increased due to forward path control signals present in QTS.

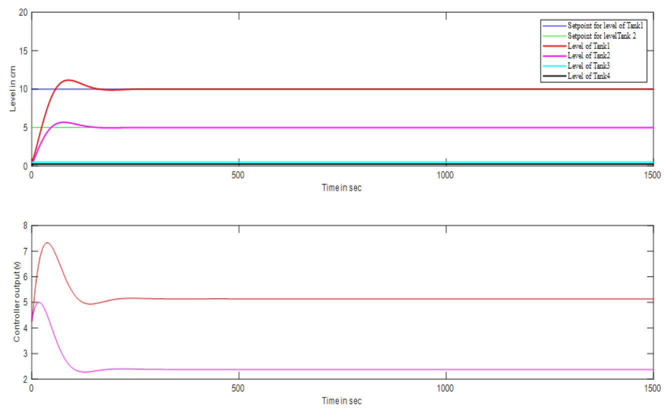

Fig. 7. Responses of PI controller with Decoupler under minimum phase condition.

Figure 8 shows the reaction of QTS controlled variables in the non-minimum phase with a set point tracking decoupler. The response is clearly seen to be free of interactions. With the help of PI controller with Decoupler, settling time was increased as well as error value also reduced. But rise time will be increased due to forward path control signals present in QTS. From the graphs, it was also found that in both operating conditions strong interactions with the PI controller occurred. But in non-minimum phase the interactions are reduced and nullified in minimum phase with the help of decouplers.

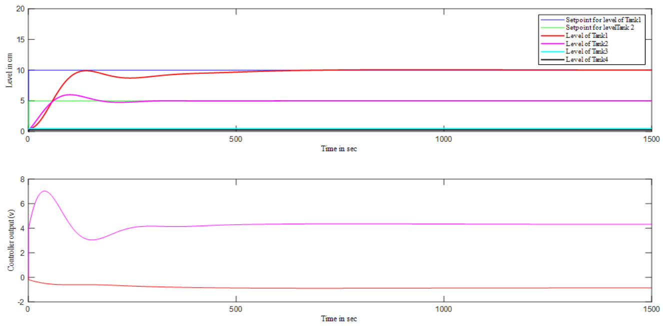

Fig. 8. Responses for PI controller plus Decoupler under non-minimum phase condition.

In this case of PI-Decoupler settling time and error value were reduced compared to the PI controller without decoupler but rise time for both operating points increased. To overcome this issue for the parameter rise time and settling time, addressed by Iterative learning controller with the PI controller, the ILC controller strongly suppresses interactions and ensures robust efficiency, but the response is over-shooted. Relevant choice of Q and L filter with tolerable overshoot will lead to better response

Table 4. Correlation of different controller's performance

Operating Points and Parameters			Controllers		
			PI	De-coupled PI	ILC PI
MP	L1	Settling time (in sec)	222	145	88
		Peak Overshoot (%)	18	11	57
		Rise Time(in sec)	42	44	6
		ISE	1750	1638	656
	L2	Settling time (in sec)	226	140	201
		Peak Overshoot (%)	34	13	23
		Rise Time(in sec)	34	35	16
		ISE	464	324	299
NMP	L1	Settling time (in sec)	560	1284	17
		Peak Overshoot (%)	0	5.3	31
		Rise Time(in sec)	84	419	2
		ISE	4276	2994	109
	L2	Settling time (in sec)	274	1286	35
		Peak Overshoot (%)	20	0	41
		Rise Time(in sec)	47	623	2.5
		ISE	477	6056	47

MP- minimum phase systems NMP-non-minimum phase systems, L1-Level 1 and L2-Level 2 of the Quadruple tank systems.

Fig. 9. shows the response of controlled variables of QTS in the minimum phase with ILC based PI controller for set point tracking. It is obviously exposed that the response is complementary from interactions as well as quantitative performance also reduced. ILC based PI controller will help to reduce the settling time and error value compared to the Decoupled PI controller but peak overshoot percentage increased due to filter added in that ILC.

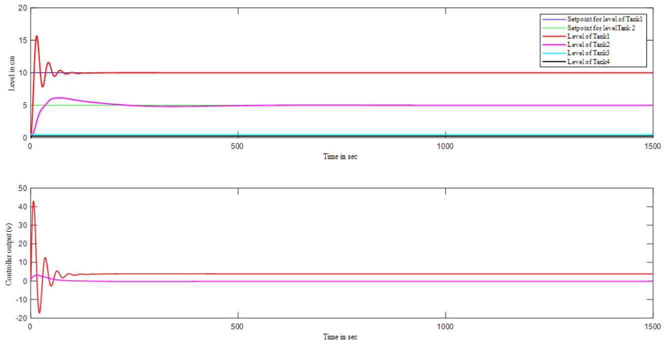

Fig. 9. Responses of ILC based PI controller under minimum phase condition.

Fig. 10. Shows the response of controlled variables of QTS in the non-minimum phase with ILC based PI controller for set point tracking. It is clearly shown that the response is free from interactions as well as quantitative performance also reduced. ILC based PI controller will help to reduce the settling time, error value, and also rise time minimised compared to Decoupled PI controller for the operating point of non-minimum phase systems.

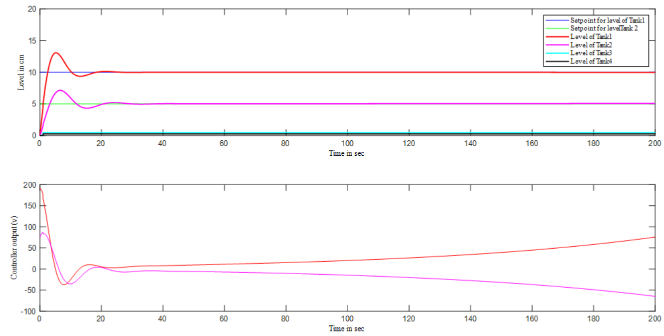

Fig. 10. Responses of ILC based PI controller under non-minimum phase condition.

In the view of the ILC based PI controller, the settling time, rise time, and error value was reduced compared to the PI controller with decoupler.

ILC will optimally tune the PI controller with the help of L and Q learning filter design as well as robustness will be increased for interactions between both minimum and non-minimum phase circumstances. Table 4. Indicates the correlation of the execution of ILC based PI controller, decoupled PI controller and PI controller,

5. CONCLUSION

The linear typical of a quadruple tank system has a multivariable zero transmission, and it is greatly additional challenging to regulate the system under non-minimum phase conditions than under minimum phase conditions. A concept of automatic adjustable PI control with ILC technology was identified in this study for the quadruple tank process. In response to plant uncertainty changes and disturbances based on the identified position model, the proposed controller may adjust the controller constraints and avoid the interaction of the system between process variables. The simulated results show that ILC solves the quadruple tank process dynamic problem and is ideal for control design under the system requirements.

The selection of the adjustment gains can be used in future optimization techniques to ensure better performance.

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