International Journal of Advanced Research
in Education & Technology (IJARET)

Vol. 4, Issue 2 (April - June 2017)

ISSN : 2394-2975 (Online)
ISSN : 2394-6814 (Print)

Design and Implementation of Controllers for Quadrupe Tank System

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Abstract

Process industries have tightly integrated processes which are non linear and have multiple manipulated and controlled variable. Level measurement plays an important role in many industries. In this paper, the level of the two lower tanks has to be controlled. Three different controllers have been designed and implemented by manipulating the motorised control valve. Conventional Controllers may not perform well because of the variations in process dynamics and disturbances around them. Such controllers cannot handle interactions. In this paper, conventional controller IMC based controller have been implemented. To reduce the interactions in the system a compensator called decoupler is designed. The requirement of high performance control systems for industrial applications has produced great research efforts for the application of modern control theory and, in particular, adaptive control. Model Reference Adaptive Control have been designed to reduce impact of variations in process dynamics and disturbances and implemented IMC based PID have been implemented in real time using decoupler and without decoupler.

Keywords

QuadrupleTank System,Decoupler, Model Reference Adaptive Control, Internal Model Control

I. Introduction

Most of industrial control problems are nonlinear and have multiple controlled variables that are common properties for the models of industrial processes to have significant uncertainties, strong interactions, and non-minimum phase behavior so it is important for control system engineer, chemical engineer to understand the non-idealities of industrial processes by carrying out experiments with a good laboratory apparatus.A control system is in the broadest sense, an interconnection of the physical components to provide a desired function, involving some type of control action with it.

The requirement of high performance control systems for industrial applications has produced great research efforts for the application of modern control theory and, in particular, adaptive control. Adaptive control is a rather recent class of control technique, although research in adaptive control has a long and vigorous history. In recent years, adaptive control has been receiving a significant amount of attention.

Level measurement is critically important for chemical process industries and the safety of the equipment they use. It also improves the plant's efficiency.Technologies such as chemical reactors, fermentation vessels, and steam and surge drums benefit from accurate level instrumentation.Storage and processing technologies such as waste sumps, neutralization, liquids storage and liquefied gas storage can benefit from level instrumentation and improve their performance.

II. Quadruple Tank System

The quadruple tank system is a multi input multi output system that could be used to analyse different control strategies. It is considered as a two double-tank process. The setup consists of four interacting tanks, two pumps and two valves. The two process inputs are the voltages v1 and v2 supplied to the two pumps. Tank 1 and tank 2 are placed below tank 3 and tank 4 to receive water flow by the action of gravity. To accumulate the outgoing water from tank 1 and tank 2 a reservoir is present in the bottom. Every tank has a valve fitted to its outlet. The action of pumps 1 and 2 is to suck water from the reservoir and deliver it to tanks based on the valve opening

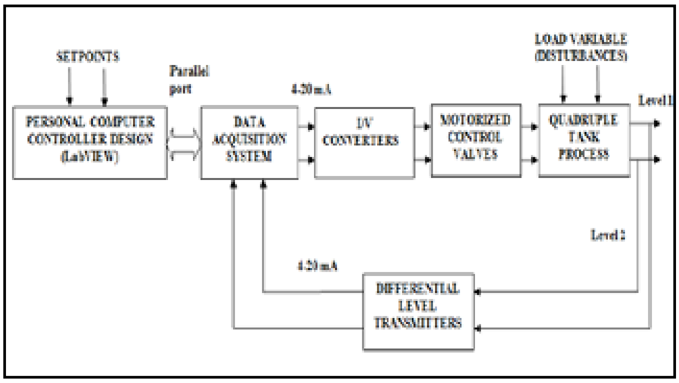

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Fig 2.1 Block Diagram of QTS

Pump 1 delivers water to tank 2 and tank 3. Similarly the pump 2 delivers water to tank 1 and tank 4.Due to gravitational force the lower tanks receive water from their corresponding upper tanks. The system aims at controlling the liquid levels in the lower tanks. The controlled outputs are the liquid levels in the lower tanks (h1, h2). The valve positions are and . These valve positions give the ratio in which the output from the pump is divided between the upper and lower tanks. The flow to the tanks can be adjusted by pump positions and flow rate can be monitored using the two rotameters. The valve position is fixed during the experiment and only the speed of pump is varied by changing the input voltage. The operation of quadruple tank system can be comprehended in two phases namely minimum phase and non- minimum phase. By adjusting the rotameter the flow to the lower and upper tanks can be varied and hence the process can be kept in minimum or non-minimum phase.

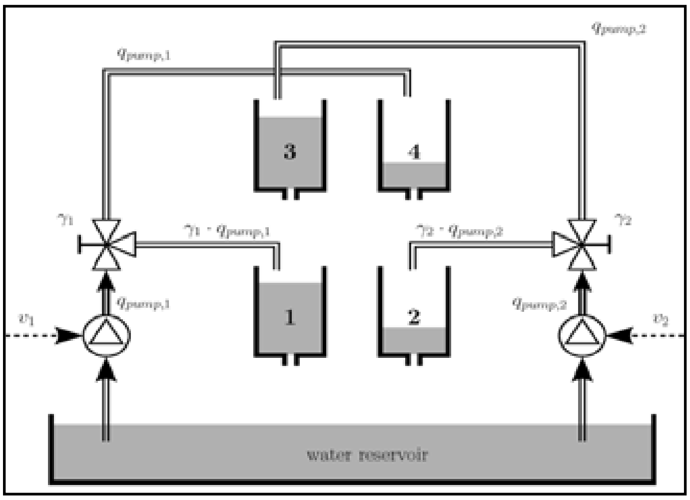

Fig 2.2 Quadruple Tank System

III. Modelling of Quadruple Tank System

The mathematical modelling of the quadruple tank system is discussed in this chapter.

A. Mathematical modelling

Modelling of a process is necessary to investigate how the behaviour of a process changes with time under influence of changes in the external disturbances and manipulated variables and to consequently design an appropriate controller . This uses two different approaches, one is experimental and the other is theoretical. In such case a representation of the process is required in order to study its dynamic behaviour. This representation is usually given in terms of a set of mathematical equations whose solution gives the dynamic behaviour of the process.
The first principle mathematical model for this process using mass balance and Bernoulli's law is obtained.

$$\frac{dx}{dt}=\begin{bmatrix} -\frac{1}{T_1} & 0 & \frac{A_3}{A_1T_3} & 0 \\ 0 & -\frac{1}{T_2} & 0 & \frac{A_4}{A_2T_4} \\ 0 & 0 & -\frac{1}{T_3} & 0 \\ 0 & 0 & 0 & -\frac{1}{T_4} \end{bmatrix}x+\begin{bmatrix} \frac{\gamma_1k_1}{A_1} & 0 \\ 0 & \frac{\gamma_2k_2}{A_2} \\ 0 & \frac{(1-\gamma_2)k_2}{A_3} \\ \frac{(1-\gamma_1)k_1}{A_4} & 0 \end{bmatrix}u$$

- (3.1)

$$y=\begin{bmatrix} k_c & 0 & 0 & 0 \\ 0 & k_c & 0 & 0 \end{bmatrix}x \text{ -(3.2)}$$

B. Quadruple tank process specification

Table 3.1 Operating points of QTP

Parameters	Values	Units
Cross section area of the tank, A_1,A_3	95	cm^2
Cross sectional area of the hole of the tank,a_1,a_2	2.01	cm^2
Cross sectional area of the hole of the tank,a_2,a_4	0.5026	cm^2
Height of tank,h_i	25	*Cm*
k_c	0.5	*V/cm*
G	981	cm/s^2

Table 3.2 Operating points for minimum and non minimum phases

(h_1^0,h_2^0)	(cm)	(3.8,2.7)	(4.0,3.0)
(h_3^0,h_4^0)	(cm)	(0.8,1.8)	(1.0,2.0)
(k_1, k_2) (γ_1,γ_2)	(cm^2/Vs)	(3.33,3.35) (0.70,0.60)	(3.14,3.29) (0.43,0.34)

On substituting the above parameter and operating point values, the values of the matrices A, B, C, D and the transfer function matrix for both minimum phase and non minimum phase are obtained as shown in the Equations (3.3) to (3.7) and Equations (3.6) to (3.12) respectively.

Minimum Phase

$$A=\begin{bmatrix} -0.24038 & 0 & 0.1310 & 0 \\ 0 & -0.2852 & 0 & 0.0873 \\ 0 & 0 & -0310.1 & 0 \\ 0 & 0 & 0 & -0.0873 \end{bmatrix} \text{- (3.3)}$$

$$B=\begin{bmatrix} 0.0245 & 0 \\ 0 & 0.02115 \\ 0 & 0.0141 \\ 0.0105 & 0 \end{bmatrix} \text{- (3.4)}$$

$$C=\begin{bmatrix} 0.50 & 0 & 0 & 0 \\ 0 & 0.50 & 0 & 0 \end{bmatrix} \text{- (3.5)}$$

$$D = 0 \text{ - (3.6)}$$

$$G\_(s)=\begin{bmatrix} \frac{0.0509}{4.16s+1} & \frac{0.0184}{(11.45s+1)(3.5s+1)} \\ \frac{0.0293}{(7.63s+1)(4.26s+1)} & \frac{0.03706}{3.506s+1} \end{bmatrix}$$

- (3.7)

Non Minimum Phase

$$A=\begin{bmatrix}-0.2342 & 0 & 0.1165 & 0\\ 0 & -0.2705 & 0 & 0.0824\\ 0 & 0 & -0.1165 & 0\\ 0 & 0 & 0 & -0.0824\end{bmatrix}\text{ - (3.8)}$$

$$B=\begin{bmatrix}0.0142 & 0\\ 0 & 0.0177\\ 0 & 0.0228\\ 0.0188 & 0\end{bmatrix}\text{ - (3.9)}$$

$$C=\begin{bmatrix}0.50 & 0 & 0 & 0\\ 0 & 0.50 & 0 & 0\end{bmatrix}\text{ - (3.10)}$$

$$D = 0 \text{ - (3.11)}$$

$$G_{+}(s)=\begin{bmatrix}\dfrac{0.03}{4.26s+1} & \dfrac{0.0349}{(12.2s+1)(3.69s+1)}\\ \dfrac{0.048}{(8.59s+1)(4.26s+1)} & \dfrac{0.0327}{3.69s+1}\end{bmatrix}$$

- (3.12)

IV. Design Of Decoupler

Increase in complexity and interactions between inputs and outputs yield degraded process behavior. Such processes are found in process industries as they arise from the design of plants that are subject to rigid product quality specifications,are more energy efficient, have more material integration, and have better environmental performance. Complexity and interaction in the system has pushed the area of process control to study investigate and develop clear knowledge for safe operation of these processes. Many active research programs are underway around the world to search useful information that will lead to find optimal solution for this problem.

A. Importance of Decoupler

Processes with only one output being controlled by a single manipulated variable are classified as single-input single-output systems. However most of the industrial processes has multiple inputs and multiple outputs. In oil refineries, the level and pressure has to be maintained but the two are dependent upon each other. There will be certain uncertainities if decoupler is not used. Hence decoupler design is an essential part of a multivariable system.

B. Multivariable decoupling control

The objective is to eliminate the effect of loop interactions. This is achieved via the specification of compensation networks known as decouplers.The role of decouplers is to decompose a multivariable process into a series of independent single loop subsystems. If such a situationcan be achieved, then compete or ideal decoupling occurs and the multivariable process can be controlled using independent loop controllers.

The figure 4.1 shows the decoupler along with the plant. Such an arrangement eliminates interaction between two loops. The need of a decoupler can be verified using input-output pairing and Relative Gain Array which will be explained below

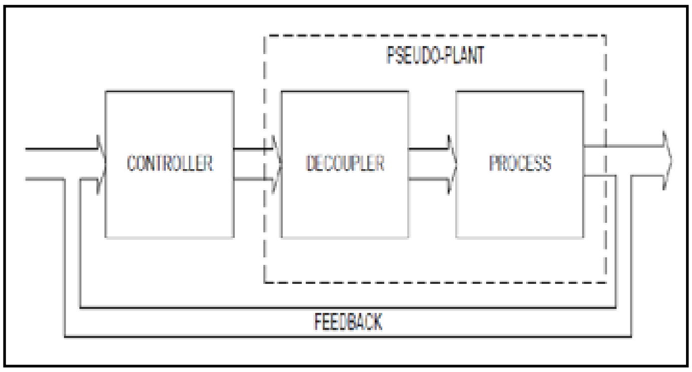

Fig 4.1 Block Diagram of the Decoupled System

In this paper, when level of one of the lower tank is settled, the water from the upper tank does not allow it to settle. This is the interaction present in this system. Hence it takes some time to settle down. The below figure shows how the decoupler has to be placed before the plant for a multivariable system.

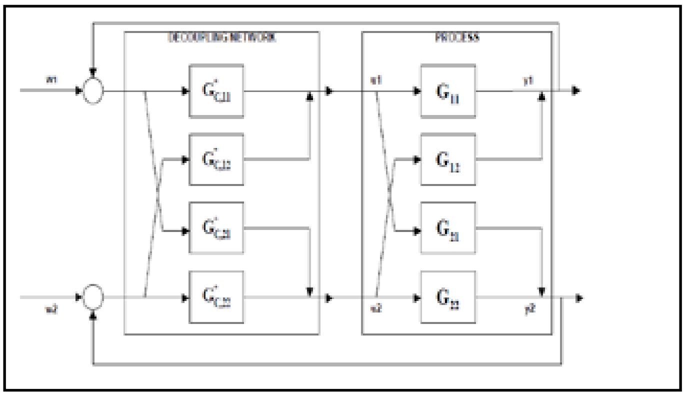

Fig 4.2 Decoupling Control System

V. Internal Model Based Controller

The conventional PID controller is still widely used in chemical and rocess industries. The advantages of using PID controller is its simplicity,easy tuning to achieve desired time domain specifications. The tuning of PID controller refers to the determination of proportional, integral and derivative gains i.e. Kp,Ki and Kd. In this chapter, the parameters are tuned using Internal Model Control.

Internal Model Control (IMC) is a commonly used technique that provides a transparent modefor the design and tuning of various types of control. In this report, we analyze various concepts of IMC design and IMC based PID controller has been designed for a plant transfer function to incorporate the advantages of PID controller in IMC. The IMC-PID controller does good set-point tracking but poor disturbance response mainly for the process which have a small time-delay/time-constant ratio. But, for many process control applications, rejection of disturbance for the unstable processes is more important than set point tracking.

A. Simulation results

The simulation is executed using MATLAB/SIMULINK. The results shows the imporatnce of decoupler. The controller parameters for the first tank is given below:

The controller parameters for the second tank is given below:

$$K_p = 1.634$$

$$\tau_I = 0.240$$

The controller parameters for the second tank is given below:

$$K_p = 1.892 \ \tau_I = 0.285$$

B. IMC based PID without decoupler

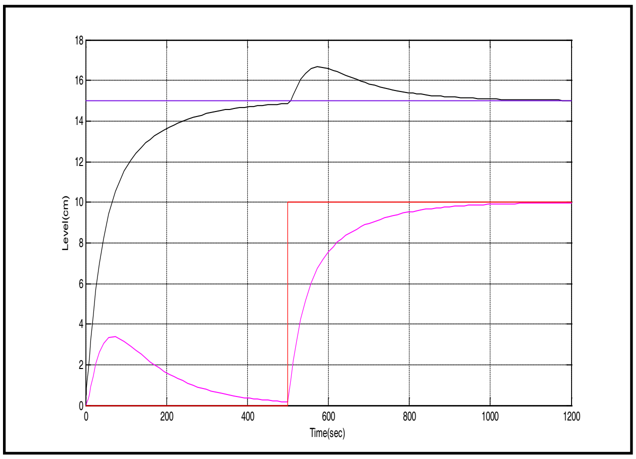

Fig 5.1 : Response of IMC based PID without Decoupler

Figure 7.1 shows when tank 2 is started(pink line) there are oscillations created in 1(black line). This is due to the interactions produced in the system. Figure 7.2 eliminates those interactions by adding decoupler to the plant.

C. IMC based PID with decoupler

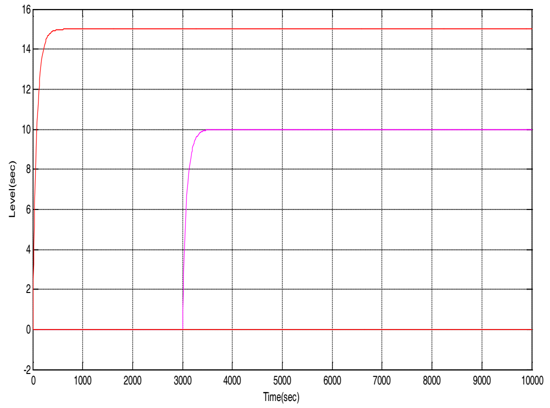

Fig 5.2 : Response of IMC based PID with Decoupler

VI. Model Reference Adaptive Control

Model Reference Adaptive Control strategy is used to design the adaptive controller that works on the principle of adjusting the controller parameters so that the output of the actual plant tracks the output of a reference model having the same reference input. In this, controller is designed by using a reference model to describe the desired characteristics of the plant to be controlled.

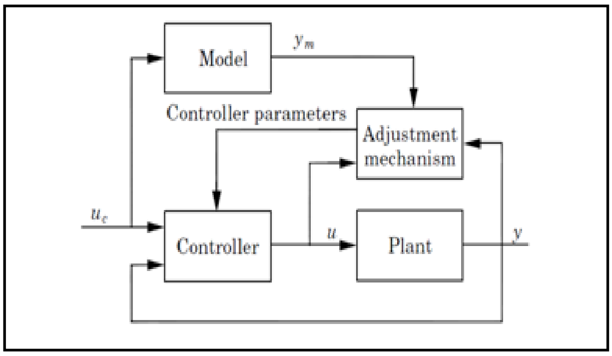

Fig 6.1 : Schematic of MRAC

A. Components of MRAC

(i) Reference model

It is used to give an idyllic response of the adaptive control system to the reference input. By choosing the structure and parameters of the reference model suitably,its outputs can be used as the desired plant response. While in principle such a model can be either linear or non linear, considerations of analytical tractability have made linear reference models more common in practice.

(ii) Controller

It is usually described by a set of adjustable parameters. In this paper only one parameter θ is used to describe the control law. The value of θ is primarily dependent on adaptation gain.

(iii) Adjustment mechanism

This component is used to alter the parameters of the controller so that actual plant could track the reference model. Mathematical approaches like MIT rule, Lyapunov theory and theory of augmented errorcanbe used to develop the adjusting mechanism. In this paper we are using MIT rule with Normalized Algorithm and the technique is then referred as Modified MIT rule. The basic block diagram of MRAC system is shown in the fig.8.1. As shown in the figure,ym(t) is the output of the reference model and y(t) is the output of the actual plant and difference between them is denoted by e(t).

B. MIT Rule

MIT rule was first developed in 1960 by the researchers of Massachusetts Institute of Technology (MIT) and used to design the autopilot system for aircrafts. MIT rule can be used to design a controller with MRAC scheme for any system.In this rule, a cost function is defined as

$$J(\theta) = \frac{1}{2}\left(e^2\theta\right)$$

- (6.1)

where e is the error between the outputs of plant and the model, and θ is the Adjustable parameter.

Parameter θ is adjusted in such a fashion so that the cost function can be minimized to zero. For this reason, the change in the parameter θ is kept in the direction of the negative gradient of J, that is

$$\frac{d\theta}{dt} = -\gamma \frac{\partial J}{\partial \theta} = -\gamma e \frac{\partial e}{\partial \theta} \text{ - (6.2)}$$

where, the partial derivative term $\frac{\partial e}{\partial \theta}$ is called as the sensitivity derivative of the system. This term indicates how the error is changing with respect to the parameter θ.

The nature of the adaptation mechanism for controlling the system performance is greatly affected by the value of adaptation gain. It is observed

that for the lower order systems, wide range of adaptation gain can be used to study the system's performance. As the order of the system increases the applicable range of adaptation gain becomes narrow.

C. Controller Algorithm

If the reference model is close to the plant we can approximate as equation (6.3)

$$\frac{bs}{a_0 s^2 + (a_1 + bk_p)s + bk_i} \approx \frac{b_{m1} s}{a_0 s^2 + a_{m1} s + a_{m2}}$$

D. Simulation results

Simulation results of MRAC tuned PI control is simulated using LABVIEW and the output response has been shown below. The simulation is done for both minimum and non minimum phase.

(i) Minimum phase

In the above response the curve(red color) settles in the setpoint which is 15 cm and when the other loop has been started the interactions between two loops causes the first loop to oscillate. After few seconds it reaches its setpoint.

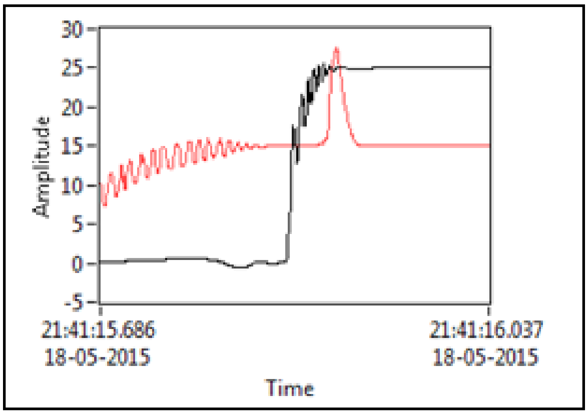

Fig.6.2 : Response without decoupler

The problem of having interaction between loops is not found here and it settles out very smoothly without any oscillations.

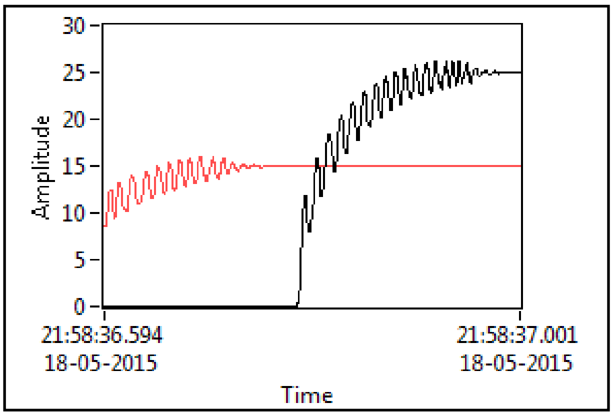

Fig.6.3 : Response of MRAC with Decoupler

(ii) Non-minimum phase

In this phase, atleast one of the zeroes of the system are present in right half of S-plane. Non minimum phase is implemented in the system by keeping the flow of water to the upper two tanks higher than the flow of water to the lower two tanks.

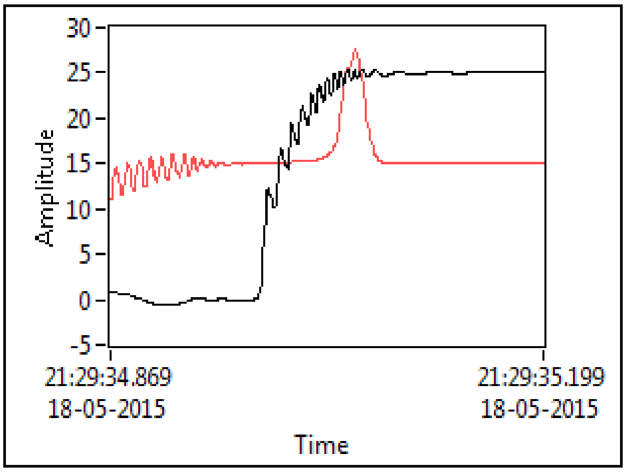

Fig.6.4 Response of MRAC without Decoupler- Non minimum phase

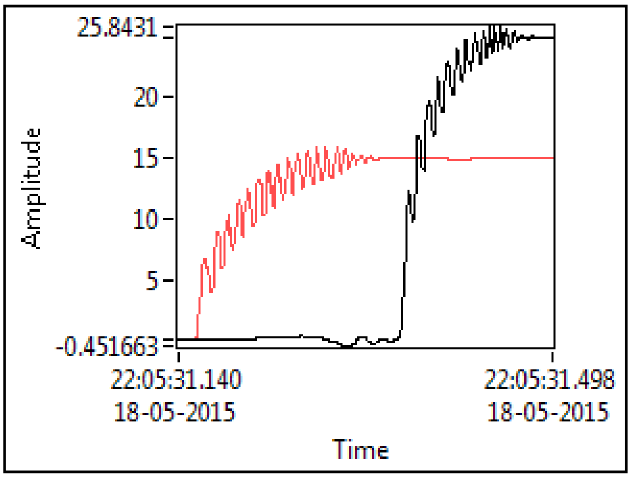

Fig6 .5 : Response of MRAC without Decoupler-Non minimum phase

VII. Real Time Implementation

Internal Model Control Based PID has been designed and implemented in real time. The time delay is calculated based on the plotting of input versus output. Here, the input given to the system is the current to the motorised control valve. The output is the level of the lower two tanks which is the controlled variable.

The current versus level plot is made using System Identification Tool box. The current value is noted for the corresponding level of the lower two tanks. The datas are then imported in System Identification Tool. From the transfer function obtained, there is no time delay present in the system. Therefore the following formulas are used to calculate the tuning parameters.

A. Tuning Parameters

The proportional gain is given as

$$k_p = \frac{\tau}{\lambda k} \quad (7.1)$$

The integral time constsnt is given as

$$\tau_I = \tau \text{ - } (7.2)$$

Where k_p = proportional gain

k = gain of the plant

λ = Time constsnt of closed loop system

τ = Time constant of the plant

τ_I = Integral Time constant

The tuning parameters for one controller is calculated below as

k = 0.0509

τ= 4.16

Let us assume the closed loop time constant as 50/sec.

$$K_P = \frac{4.16}{50 * 0.0509}$$

$$K_P = 1.634$$

$$\tau_I = 0.240$$

The tuning parameters for one controller is calculated below as

k = 0.03706

τ= 3.506

Let us assume the closed loop time constant as 50/sec.

$$K_P = \frac{3.506}{50 * 0.03706}$$

$$K_P = 1.892$$

$$\tau_I = 0.2852$$

Where = proportional gain
k = gain of the plant

B. Real Time Implementation without Decoupler

The parameter values obtained above is fixed in the respective controller and the process is started. Implementation is done only for minimum phase. The flow of water to the lower tanks are made higher than the upper tanks by adjusting the rotameter attached to each tank.

(i) Controller 1 Output

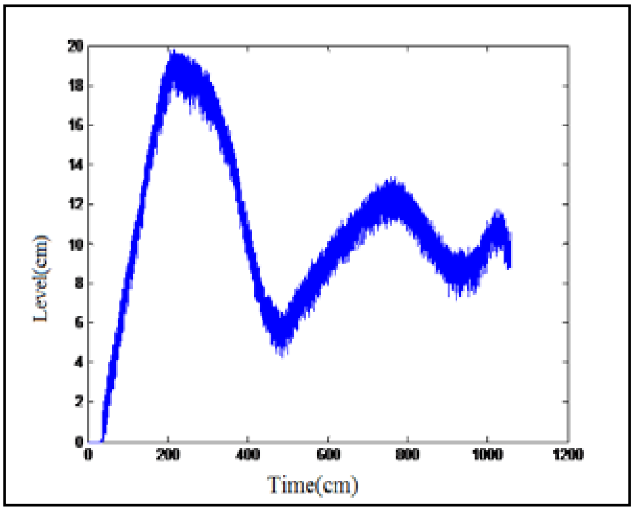

Fig 7.1 : Response of Tank 1 controller without Decoupler

From figure , there are oscillations in the system which is due to the interaction of the tanks. The choice of the proportional gain and integral time constant plays the key role. If λ is less than 10 then the system takes more time to settle. Here the λ is taken as 50 so that the proportional gain is less and settles down faster than the previous case.

(ii) Controller 2 Output

From figure, it is clear that there are interactions present in the system, which prevents the settling time of one another and the system oscillates and finally settles down later. To reduce the interactions, a compensating network called as decoupler is designed.

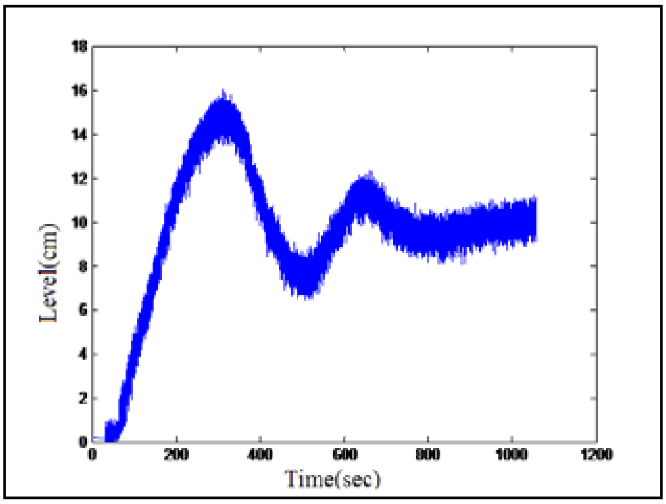

Fig 7.2 : Response of Tank 2 controller without Decoupler

C. Real Time Implementation Using Decoupler

(i) Controller 1 Output

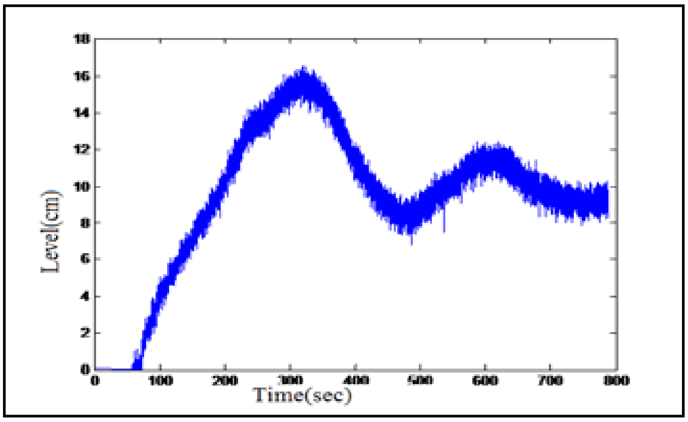

Fig 7.3 : Response of Tank 1 controller with Decoupler

Comparing figure (7.1) and figure (7.2) , the oscillations produced in the system with decoupler is less than the one without Decoupler. Another point is that the plant with decoupler settles down faster than the one without decoupler.

(ii) Controller 2 Output

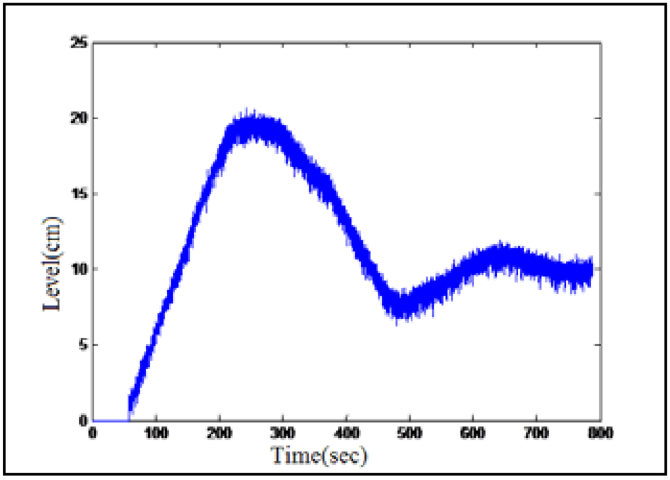

Fig 7.4 : Response of Tank 1 controller with Decoupler

From the results obtained, it is clear that by using decoupler the interactions in the system have been reduced and the plant settles down faster than the plant without decoupler .

VIII. Conclusion

The controlling of multivariable system is a very challenging task to perform. In this project, the level of the Quadruple tank system is controlled using various control schemes such as IMC based tuning and MRAC. Conventional controller, IMC based PID tuning and Model Reference Adaptive Control have been simulated. It has been compared and the results have been discussed.

In real time implementation,IMC based tuning method has some oscillations that is due to the interactions in the system. These interactions may cause uncertainity to the process. Hence, IMC based tuning with decoupler is implemented which minimizes the interactions that are caused in conventional controllers.

IX. Future Work

This paper can be extended to implement Neural Network model and Fuzzy Logic within MRAC in order to obtain better performance of MRAC. This provides high level of human understanding.

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