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Implementation of Controllers for Quadruple Tank System

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Abstract: - **In a quadruple tank system, the process of maintaining the level of two tanks is achieved with a high settling time leading the system to be complex by having a slow response. To obtain a system with minimum settling time thereby reducing the complexity, the approach is done by proposing an algorithm using an MPC (Model Predictive Control), MRAC (Model Reference Adaptive Control) and SMC (Sliding Mode Controller) to achieve it with minimum peak overshoot. Thus, the design of an algorithm for a quadruple tank system (QTS) is to be carried out in this phase of the paper.**

Keywords - MPC, MRAC, SMC, QTS.

I. INTRODUCTION

The quadruple tank system is a benchmark system used to analyze the nonlinear effects in multivariable process. This helps in realizing the multi loop systems in industries [1]. The quadruple tank process is thus used to demonstrate coupling effects and performance limitations in multivariable control systems. The multivariable dynamic property in a quadruple tank system is the way in which each pump affects both the outputs of the system. The quadruple tank system is widely used in visualizing the dynamic interactions and non-linearity's exhibited in the operation of power plants, chemical industries and biotechnical fields[2]. These applications are Multi Input Multi Output (MIMO) systems. The control of such interacting multivariable processes is of great interest in process industries.

II. HARDWARE DESCRIPTION

2.1 BLOCK DIAGRAM

The common block diagram for quadruple tank process is given below in Fig 2.1.

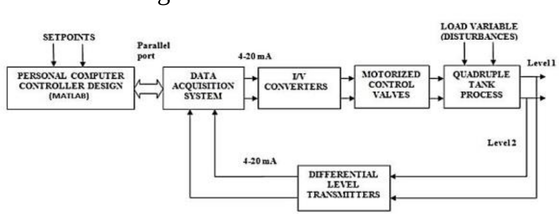

Fig 2.1 Block diagram of Quadruple Tank System

The process inputs are u1 and u2 input voltage to pumps (0-10) V and the outputs are y1 and y2 voltages from level measurement devices (0-10)V. The strategies to control the level of the lower two tanks with inlet flow rates. The output of each pump is split into two using a three-way valve[3]. Thus each pump output goes to two tanks, one lower and another upper, diagonally opposite and the ratio of the split up is controlled by the position of the valve. With the change in position of the two valves, the system can be appropriately placed either in the minimum phase or in the non-minimum phase. Let the parameter γ be determined by how the valves are set.

The Quadruple tank setup is shown in the Fig 2.2.

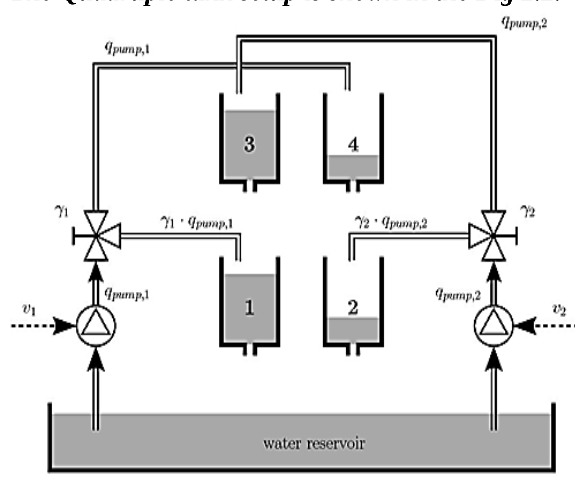

Fig 2.2 Structure of Quadruple Tank System

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III. SOFTWARE DESCRIPTION:

3.1 INTRODUCTION TO MATLAB

The MATLAB stands for Matrix Laboratory. MATLAB was written originally to provide easy access to matrix software developed by the LINPACK (linear system package) and EISPACK (Eigen system package) projects[3]. MATLAB is a high-level language and interactive environment that enables to perform computationally intensive tasks faster than with traditional programming languages such as C, C++, and FORTRAN.
MATLAB is a high-performance language for technical computing. It integrates computation, visualization, and programming environment. MATLAB is an interactive system whose basic data element is an array that does not require dimensioning. It also has easy to use graphics commands that make the visualization of results immediately available. Specific applications are collected in packages referred to as toolbox. There are toolboxes for signal processing, symbolic computation, control theory, simulation, optimization, and several other fields of applied science and engineering.

3.2 SIMULINK

Simulink is an environment for multi domain simulation and Model-Based Design for dynamic and embedded systems. It provides an interactive graphical environment and a customizable set of block libraries that the design simulates, implement, and test a variety of time-varying systems, including communications, controls, signal processing, video processing, and image processing.
Simulink Control Design designs and analyses control systems modeled in Simulink. Automatic tuning of PID controller gains adjusted in order to meet performance requirements. Simulink Control Design provides tools for computing simulation-based frequency responses without modifying the model. A graphical user interface (GUI) design and analyze arbitrary control structures modeled in Simulink, such as cascaded, pre filter, regulation, and multi loop architectures the blocks used in MATLAB Simulink are described.

VI. MATHEMATICAL MODELLING OF QUADRUPLE TANK SYSTEM

4.1 MATHEMATICAL MODELLING

Modelling of a process is necessary to investigate how the behavior of a process changes with time under influence of changes in the external disturbances and manipulated variables and to consequently design an appropriate controller[2]. 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 behavior. This representation is usually given in terms of a set of mathematical equations whose solution gives the dynamic behavior of the process. The first principle mathematical model for this process using mass balance and Bernoulli's law is described in the Equations (4.1) to (4.4).

$$\frac{dh_1}{dt} = -\frac{a_1}{A_1}\sqrt{2gh_1} + \frac{a_3}{A_1}\sqrt{2gh_3} + \frac{\gamma_1 k_1}{A_1}\upsilon_1 \tag{4.1}$$

$$\frac{dh_2}{dt} = -\frac{a_2}{A_2}\sqrt{2gh_2} + \frac{a_4}{A_2}\sqrt{2gh_4} + \frac{\gamma_2 k_2}{A_2}\upsilon_2 \tag{4.2}$$

$$\frac{dh_3}{dt} = -\frac{a_3}{A_3}\sqrt{2gh_3} + \frac{(1-\gamma_2)k_2}{A_3}\upsilon_2 \tag{4.3}$$

$$\frac{dh_4}{dt} = -\frac{a_4}{A_4}\sqrt{2gh_4} + \frac{(1-\gamma_1)k_1}{A_4}\upsilon_1 \tag{4.4}$$

where

A_i denotes cross-sectional area of tank, cm^2

a_i denotes cross sectional area of the outlet hole, cm^2

γ_i denotes fraction of water flowing to tank i from pump i

h_i denotes water level in tank, cm

g denotes acceleration due to gravity, cm/s^2

The vector matrix form of the state space model is obtained as given by the equations (4.5) and (4.6)

$$\dot{X} = AX + BV \tag{4.5}$$

$$Y = CX + DV \tag{4.6}$$

Therefore we get the state equations as given in the equations (4.7) to (4.10)

$$Y = CX + DV \tag{4.6}$$

Therefore we get the state equations as given in the equations (4.7) to (4.10)

$$\dot{x}_1 = -\frac{a_1}{A_1}\sqrt{2gh_1} + \frac{a_3}{A_1}\sqrt{2gh_3} + \frac{\gamma_1 k_1}{A_1}\upsilon_1 \tag{4.7}$$

$$\dot{x}_2 = -\frac{a_2}{A_2}\sqrt{2gh_2} + \frac{a_4}{A_2}\sqrt{2gh_4} + \frac{\gamma_2 k_2}{A_2}\upsilon_2 \tag{4.8}$$

$$\dot{x}_3 = -\frac{a_3}{A_3}\sqrt{2gh_3} + \frac{(1-\gamma_2)k_2}{A_3}\upsilon_2 \tag{4.9}$$

$$\dot{x}_4 = -\frac{a_4}{A_4}\sqrt{2gh_4} + \frac{(1-\gamma_1)k_1}{A_4}\upsilon_1 \tag{4.10}$$

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V. DESIGN OF MODEL PREDICTIVE CONTROLLER

5.1 INTRODUCTION TO MODEL PREDICTIVE CONTROLLER

Model predictive control (MPC) is an advanced method of process[8] control that has been in use in the process industries in chemical plants and oil refineries since the 1980s. In recent years it has also been used in power system balancing models. Model predictive controllers rely on dynamic models of the process, most often linear empirical models obtained by system identification. The block diagram of model predictive controller is given below in Fig 5.1. The current timeslot to be optimized, while keeping future timeslots in account. This is achieved by optimizing a finite time-horizon, but only implementing the current timeslot. MPC has the ability to anticipate future events and can take control actions accordingly. PID and LQR controllers do not have this predictive ability. MPC is nearly universally implemented as a digital control, although there is research into achieving faster response times with specially designed analog circuitry which is given in detail by George Stephanopoulos (1984). However, as an initial level of application to achieve a control for quadruple tank system, it is better to check the stability by applying model predictive control algorithm. This is done because the operation of this process takes place by optimizing the present time slot considering the future possible timeslot cases. Thus, the MPC algorithm is employed here to control the quadruple tank system. A process model is used to predict the current values of the output variables. The residuals, the differences between the actual and predicted outputs, serve as the feedback signal to a Prediction block. The predictions are used in two types of MPC calculations that are performed at each sampling instant set-point calculations and control calculations. Inequality constraints on the input and output variables, such as upper and lower limits, can be included in either type of calculation. The MPC configuration is similar to both the internal model control, because the model acts in parallel with the process and the residual serves as a feedback signal. However, the coordination of the control and set-point calculations is a unique feature of MPC. Furthermore, MPC has a much greater impact on industrial practice than IMC or Smith predictor, because it is more suitable for constrained MIMO control problems [7]. The set points for the control calculations, also called targets, are calculated from an economic optimization based on a steady-state model of the process, traditionally linear model. Typical optimization objectives include maximizing a profit function, minimizing a cost function, or maximizing a production rate

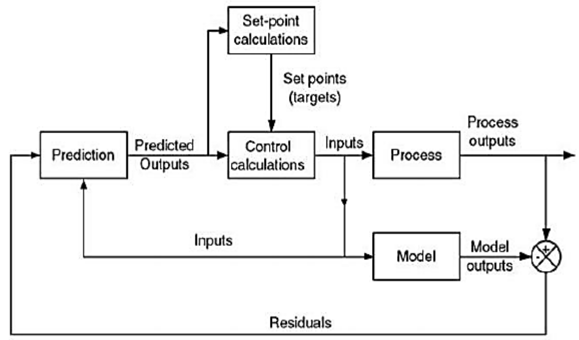

Fig 5.1 Block Diagram of Model Predictive Controller

The set points for the control calculations, also called targets, are calculated from an economic optimization based on a steady-state model of the process, traditionally linear model. Typical optimization objectives include maximizing a profit function, minimizing a cost function, or maximizing a production rate. The optimum values of set points change frequently due to varying process conditions, especially changes in the inequality. The constraint changes are due to variations in process conditions, equipment, and instrumentation, as well as economic data such as prices and cost. The MPC calculations are based on current measurements and predictions of the future values of the outputs.

VI. DESIGN OF MODEL REFERENCE ADAPTIVE CONTROL

6.1 INTRODUCTION

A control system is a device that regulates or controls the dynamics of any other plant or process and it follows the structure depicted in Fig 6.1. Adaptive control is one of the widely used control strategies to design advanced control systems for better performance and accuracy. As compared to the simple structured fixed gain PID controllers, adaptive controllers are very effective to handle the unknown parameter variations and environmental changes. The constraint changes are due to variations in process conditions, equipment, and instrumentation, as well as economic data such as prices and cost. The MRAC calculations are based on current measurements and predictions of the future values of the outputs.

The adjustment mechanism, 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 error can be 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 [6].

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6.2 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 [8].

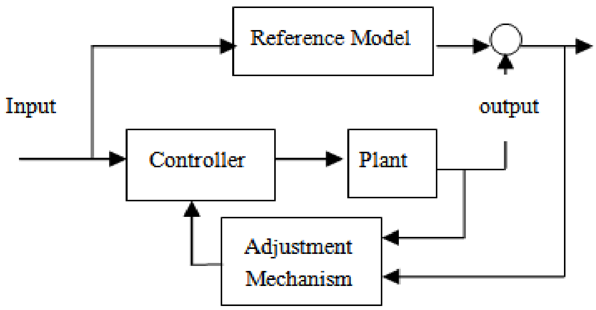

Fig 6.1 Schematic Diagram of MRAC

In this, controller is designed by using a reference model to describe the desired characteristics of the plant to be controlled. The adjustment mechanism provides flexibility for the users.

VII. DESIGN OF SLIDING MODE CONTROLLER

7.1 INTRODUCTION

In the theoretical description of sliding modes, the system stays confined to the sliding surface and need only be viewed as sliding along the surface as depicted in fig 7.1. However, real implementations of sliding mode control approximate this theoretical behavior with a high-frequency and generally non-deterministic switching control signal that causes the system to "chatter"[6] in a tight neighborhood of the sliding surface[7].

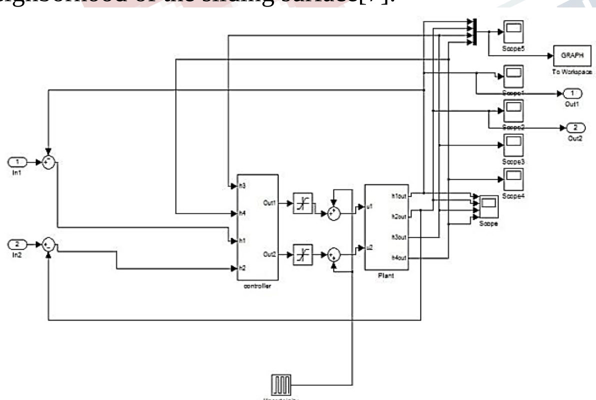

Fig 7.1 Schematic Diagram of sliding mode controller

In fact, although the system is nonlinear in general, the idealized(i.e., non-chattering) behavior of the system. Intuitively, sliding mode control uses practically infinite gain to force the trajectories of a dynamic system to slide along the restricted sliding mode subspace. Trajectories from this reduced-order sliding mode have desirable properties (e.g., the system naturally slides along it until it comes to rest at a desired equilibrium).

Because the control can be as simple as a switching between two states (e.g., "on"/"off" or "forward"/"reverse"), it need not be precise and will not be sensitive to parameter variations that enter into the control channel[6]. Additionally, because the control law is not a continuous function, the sliding mode can be reached in finite time (i.e., better than asymptotic behavior). Under certain common conditions, optimality requires the use of bang–bang control; hence, sliding mode control describes the optimal controller for a broad set of dynamic systems[9]. In particular, because actuators have delays and other imperfections, the hard sliding-mode-control action can lead to chatter, energy loss, plant damage, and excitation of unmodeled dynamics. Continuous control design methods are not as susceptible to these problems and can be made to mimic sliding-mode controllers.

$$\mathbf{x} = \begin{bmatrix} u_e \\ \frac{d}{dt}u_e \end{bmatrix} = \begin{bmatrix} U_r - u_c \\ -\frac{d}{dt}u_c \end{bmatrix} \tag{7.1}$$

According to LQ design the cost function (7.1) is minimized by solving the well known Riccati equation to achieve the optimal feedback gain for subsystem

$$J = \int_{t_s}^{\infty} (x_1^T Q x_1 + 2x_1^T N x_2 + x_2^T R x_2)\,dt. \tag{7.2}$$

Where ts (can be assumed zero) is the time at which sliding mode begins.

(For simplicity, N = 0 is assumed.)

$$K_{LQ} = R^{-1} A_{12}^T P \tag{7.3}$$

Where P > 0 is a unique solution of the following Riccati equation

$$PA_{11} + A_{11}^T P - PA_{12} R^{-1} A_{12}^T P + Q = 0 \tag{7.4}$$

The optimal switching plane is written using the solution of this Riccati equation [5] as

$$K_{RS} = R_a^{-1}(B_a^T P_a + N_a^T),\ \sigma = x_2 + K_{RS} x_2 \tag{7.5}$$

The control law is chosen as follows:

$$u_k = \begin{cases} u_{eqk} & (\|u_{eqk}\| < u_{\max}) \\ u_{\max} \dfrac{u_{eqk}}{\|u_{eqk}\|} & (\|u_{eqk}\| > u_{\max}) \end{cases} \tag{7.6}$$

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Thus, the sliding mode control had shown effective response in determining the most suitable control algorithm for the process of controlling a quadruple tank system

VIII. RESULT AND DISCUSSION

8.1 CLOSED LOOP RESPONSE OF MPC CONTROLLER

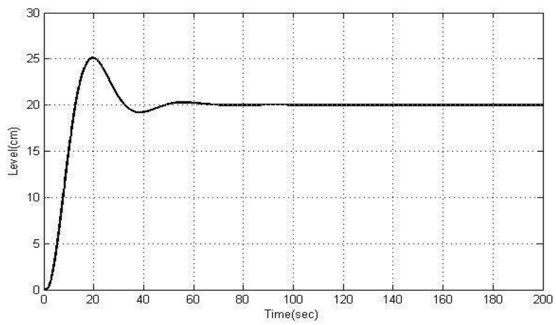

Fig 8.1.1 Closed response of MPC controller (Tank1)

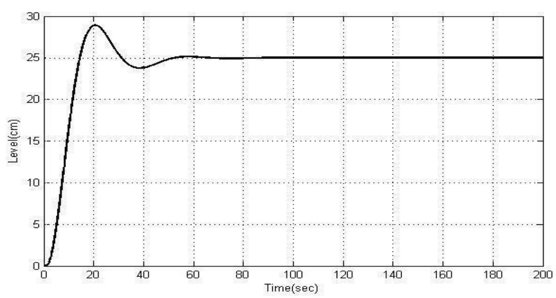

Fig 8.1.2 Closed response of MPC controller (Tank 2)

The above two graphs in fig 8.1.1 and 8.1.2 represents the closed loop responses of the two tanks with MPC controller implementation respectively. The peak time obtained when implementing this controller is 20 seconds and it settles within 140 seconds. The rising time in this response is 8.4 seconds. Since the settling time and peak time are higher, we go for MRAC control algorithm.

8.2 OUTPUT RESPONSE OF MRAC CONTROLLER

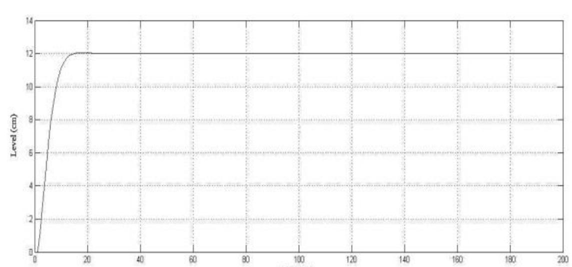

Fig 8.2.1 Output response of MRAC controller (Tank 1)

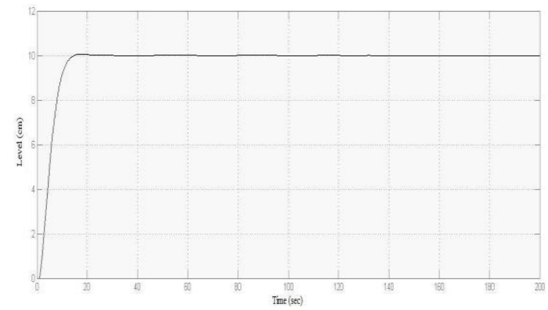

Fig 8.2.2 Output response of MRAC controller (Tank 2)

The above two graphs in the fig 8.2.1 and 8.2.2 represents the closed loop responses of the two tanks with MRAC controller implementation respectively. The peak time obtained when implementing this controller is 10 seconds and it settles within 100 seconds. The rising time in this response is 16.8 seconds. Since the settling time and peak time are higher, we go for sliding mode control algorithm control algorithm.

8.3 OUTPUT RESPONSE OF SLIDING MODE CONTROLLER

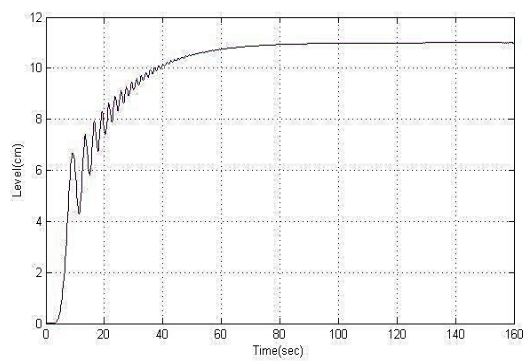

Fig 8.3.1 Output response of Sliding mode controller (Tank 1)

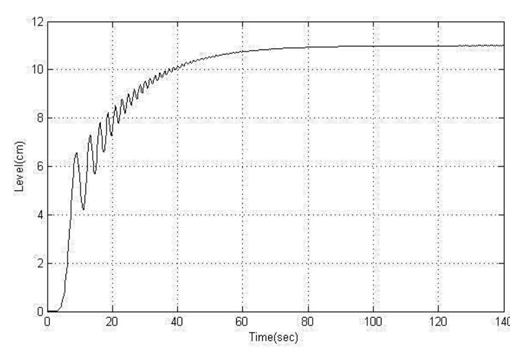

Fig 8.3.2 Output response of Sliding mode controller (Tank 2)

The above two graphs in fig 8.3.1 and 8.3.2 represents the closed loop responses of the two tanks with SMC controller implementation. The peak time obtained when implementing this controller is 6 seconds and it settles within 11 seconds. The rising time in this response is 33.4 seconds. of many algorithms being implemented for the above set up in fig 2.2. The sliding mode control algorithm proves to be more efficient than the other control algorithms. The comparison of the responses of implementing various control algorithms for a quadruple tank system is tabulated below in table 8.1.

TABLE 8.1 COMPARISON OF CONTROLLERS PERFORMANCE

CONTROLLER PARAMETERS	MPC CONTROLLER	MRAC BASED PID CONTROLLER	SLIDING MODE CONTROLLER
Peak Time (Sec)	20	10	6
Settling Time(Sec)	140	100	11
Rise time (Sec)	8.4	16.8	33.4
Maximum Overshoot (%)	0.24	0.13	0

IX. CONCLUSION

In this paper the different controllers like Model Predictive Controller (MPC), Model reference adaptive control (MRAC) based and sliding mode controller (SMC) are designed and simulated using MATLAB. By comparing the controller parameters, it is found that sliding mode controller gives better result. Sliding mode controller has minimum settling time without peak over shoot. So that sliding mode controller yields most suitable controller technique for quadruple tank system in industrial applications.

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