CHAPTER 1

INTRODUCTION

This chapter introduces and explains the project topic "analyzing and controlling a CSTR using state space approach". A background study on this topic is highlighted followed by the problem statement, objectives and finally the scope of study.

1.1 Background of Study

Being an engineer when we use to have a discussion about the industries, we take into consideration few concepts in our mind such as Safety, Environmental protection, Equipment protection, Smooth plant operation and production rate, product quality, Profit optimization, Monitoring and diagnosis. In order to meet these process objectives, several control strategies and diagnosis techniques are applied in the industries.

The main purpose of this topic is to "analyzing and modeling of "continuous stirred tank reactor by using state-space approach". A background study of this topic is controlling of the tank's variables such as concentration, temperature, flow, volume and level, etc can be carried out by using computer software such as MATLAB/SIMULINK with control system tool box process plant.

Stirred tank reactors are units very often used in industry, especially in chemical and biochemical divisions. Continuous Stirred Tank Reactor (CSTR) is widely used for control because input flow of the reactant or cooling liquid can be controlled easily. From the system engineering point of view CSTR belong to the class of the nonlinear systems with continuous distributed parameters. Mathematical models of these reactors are described by a set of nonlinear ordinary differential equations (ODEs). Computer simulation is very often used at present as it has advantages over an experiment on a real system, which is sometimes not feasible and can be dangerous or time and money demanding. Some simplifications, modeling and simulation can be done. The goal of this work is to simulate the behavior and control of a real reactor.

1.2 Problem Statement

- Today's industries focus only on stability in plant control system. Robustness, optimality and adaptively are often overlooked.
- Conventional control approaches are widely used for controlling a process. This project investigates the liability of modern control concepts being plant process problems, e.g. concentration, flow, level, volume, and temperature etc.
- The modeling of plant control system presently only using first-order state space equations, providing only limited capabilities in modern plant control.
- Study on second-order state space equations is done in this project to enable more flexibility in plant process control, more states can be controlled.

1.3 Objectives of the study

The main objective of this project is to design and analyze a controller for a continuous stirred tank reactor system via state space approach. In doing so, the following objectives below are set:

- To theoretically apply the concepts of modern control engineering in plant process control system.
- Analysis of continuous stirred tank reactor (CSTR) via state-space approach
- Modeling of the continuous stirred tank reactor(CSTR) via state-space approach

1.4 Scope of study

The scope of this project is on the continuous stirred tank reactor. Therefore, this project requires detailed study of the continuous stirred tank reactor. Besides that following should be also achieved:

- Modeling a plant process control system on MATLAB and SIMULINK.
- Designing and implementing observer and controller strategies for plant processes.

CHAPTER 2

LITERATURE REVIEW

This section reviews the critical points and theories covered in this topic.

2.1 Modern Control Theory

- Modern control theory utilizes the time-domain *state space* representation, a mathematical model of a physical system as a set of input, output and state variables related by first-order differential equations.
- To abstract from the number of inputs, outputs and states, the variables are expressed as vectors and the differential and algebraic equations are written in matrix form.
- The state space representation (also known as the "time-domain approach") provides a convenient and compact way to model and analyze systems with multiple inputs and outputs.
- Unlike the frequency domain approach, the use of the state space representation is not limited to systems with linear components and zero initial conditions.
- "State space" refers to the space whose axes are the state variables. The state of the system can be represented as a vector within that space.[1]

2.2 Process Control

Process control is a statistics and engineering field that deals with architectures, mechanisms, and algorithms these are the specific process for controlling the output [4]

For example, increasing the temperature of an iron rod is a process that has the specific, to get the approximate value and maintain defined variables like temperature pressure and etc kept constant over time. Here, the temperature can be controlled. At the same time, it is the input variable since it is measured by a thermometer and used to decide whether to heat or not to heat. The required temperature is the set point. The state of the heater (e.g. the setting of the valve allowing hot water to flow through it) is called the manipulated variable since it is subject to control actions.

A commonly used control device called a programmable logic controller, or a PLC is used to read a set of analog and digital inputs, apply a set of logic commands, and generate a set of digital and analog outputs. Using above example, the iron rod temperature would be an input to the PLC. The logical statements would compare the set point to the input temperature and determine whether more or less heating was necessary to keep the temperature constant. A PLC output would then either open or close the hot water valve, an incremental amount, depending on whether more or less hot water was needed. Larger more complex systems can be controlled by a Distributed Control System (DCS).

In practice, process control systems can be characterized as one or more of the following forms:

Discrete – Found in many manufacturing, motion and packaging applications. Robotic assembly, such as that found in automotive production, can be characterized as discrete process control. Most discrete manufacturing involves the production of discrete pieces of product, such as metal stamping.

Batch – Some applications require that specific quantities of raw materials be combined in specific ways for particular durations to produce an intermediate or end result. Batch processes are generally used to produce a relatively low to intermediate quantity of product per year (a few pounds to millions of pounds).

Continuous – Often, a physical system is represented through variables that are smooth and uninterrupted in time. Continuous processes in manufacturing are used to produce very large quantities of product per year (millions to billions of pounds).

Application having element of discrete, batch and continuous process control are often called hybrid applications. [3][7]

2.3 Mechanism of Process Control

Measurements are made via sensors, in which the analogue signals are converted into digital for plant control. A controller then examines the error present to determine the amount of actions required to be taken. The inputs of measured variable and desired value for the variable are necessary, in which all these control operations are performed via computers using software such as MATLAB and Simulink. [2]

The final element e.g. valves, pumps and motors exert direct influence on the process and bring the controlled variable into the desired value by accepting inputs from the controller before converting and performing proportional operation on the process plant. The flow diagram of the entire process is shown in **Figure 1**.

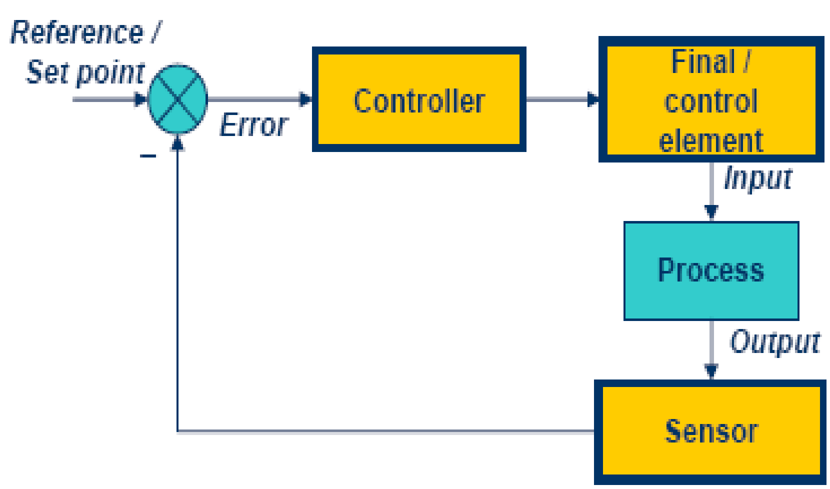

Figure 1 Flow diagram of a process control in a plant.

The desire conditions e.g. pressure and temperature in the process plant is maintained by adjusting selected variables in the system. Such feedback control is carried out by deviating outputs of the system in order to influence an input (correction) back into the system. [2]

An example of a feedback control that can be carried out in the maintaining the pressure in a process plant is shown in **Figure 2**.

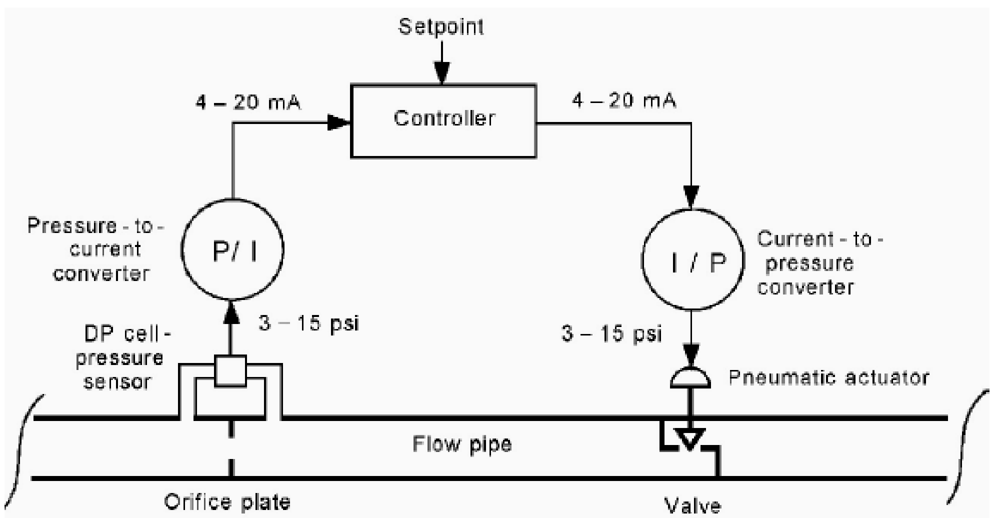

Figure 2 Example of feedback control in a process plant

2.4 States-Space Representation

In a state space representation is a mathematical model of a physical system as a set of input, output and state variables. To abstract from the number of inputs, outputs and states, the variables are expressed as vectors and the differential and algebraic equations are written in matrix form (the last one can be done when the dynamical system is linear and time invariant). The state space representation (also known as the "time-domain approach") provides a convenient and compact way to model and analyze systems with multiple inputs and outputs [1]

In the state-space representation of plant control system, the entire system is expressed in the form shown in **Figure 3**.

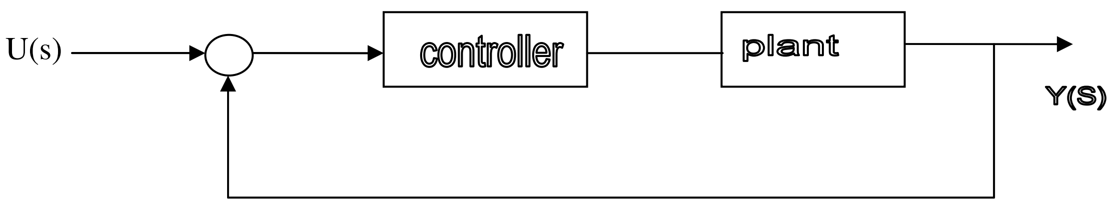

Figure 3 State-space representation of a plant control system

To model a plant control system using state-space approach, the transfer function of the process plant must first be obtained via the empirical modeling method (using system identification). In this method the output, y is known and experiments are carried out to obtain the transfer function. [1]

With the transfer function obtained, the states are then estimated and finally the state-space equations can be obtained in the following form:

$$\dot{x}=Ax + Bu$$

$$y = Cx + Du$$

A working control system using state-space approach shall result in the following response shown in **Figure 4**.

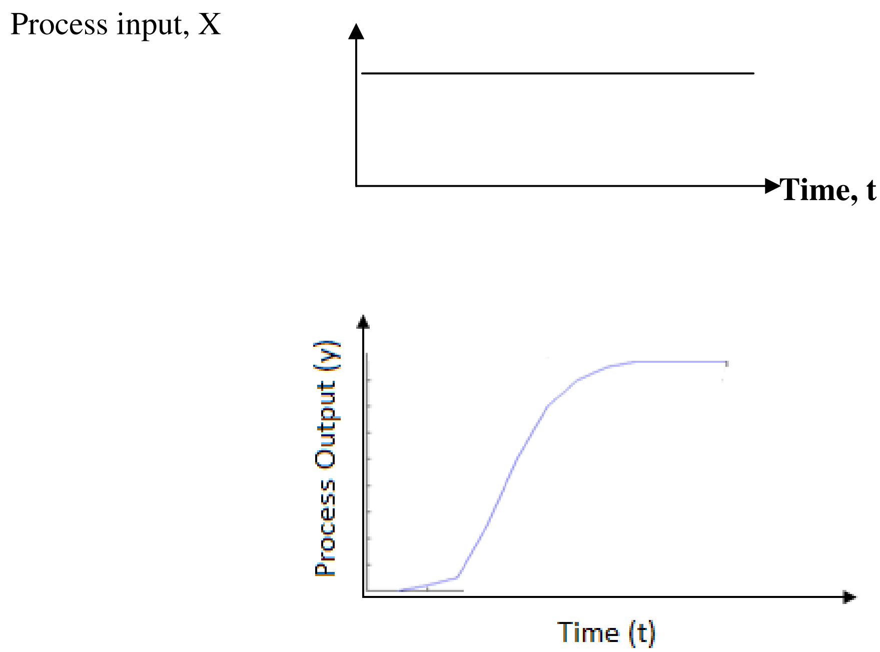

Figure 4 Response of a working control system

2.5 Continuous Process

2.5.1 Continuous Stirred Tank Reactor

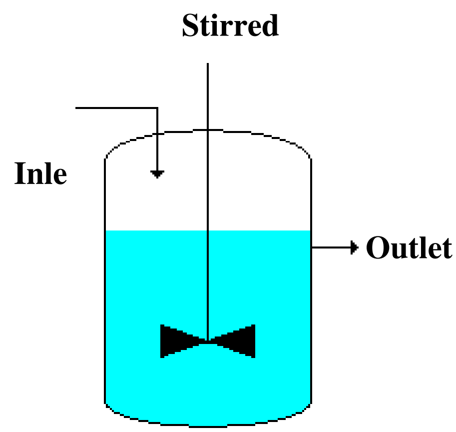

Figure 5: Continues stirred Tank Reactor (CSTR)

Continuous-flow stirred-tank reactors in series are simpler and easier to design for isothermal operation than are tubular reactors. Reactions with narrow operating temperature ranges or those requiring close control of reactant concentrations for optimum selectivity benefit from series arrangements. If severe heat-transfer requirements are imposed, heating or cooling zones can be incorporated within or external to the CSTR. For example, impellers or centrally mounted draft tubes circulate liquid upward, then downward through vertical heat-exchanger tubes. In a similar fashion, reactor contents can be recycled through external heat exchangers. [4]

The CSTR configuration is widely used in industrial applications and in wastewater treatment units (i.e. activated sludge reactors). The continuous stirred-tank reactor (CSTR), also known as vat- or back mix reactor, is a common ideal reactor type in chemical engineering. A CSTR often refers to a model used to estimate the key unit operation variables when using a continuous-agitated-tank reactor to reach a specified output. The mathematical model works for all fluids: liquids, gases, and slurries.

The behavior of a CSTR is often approximated or modeled by that of a Continuous Ideally Stirred-Tank Reactor (CISTR). All calculations performed with CISTRs assume perfect mixing. If the residence time is 5-10 times the mixing time, this approximation is valid for engineering purposes. The CISTR model is often used to simplify engineering calculations and can be used to describe research reactors. In practice it can only be approached, in particular in industrial size reactors. [6]

Integral mass balance on number of moles N_i of species i in a reactor of volume V.

$$[Accumulation] = [in] - [out] + [generation]$$

$$\frac{dN_i}{dt} = F_{io} - F_i + V\nu_i r_i \tag{1}$$

Where F_{io} is the molar flow rate inlet of species i, F_i the molar flow rate outlet, and ν_i stoichiometric coefficient. The reaction rate, r, is generally dependent on the reactant concentration and the rate constant (k). The rate constant can be figured by using the Arrhenius temperature dependence. Generally, as the temperature increases so does the rate at which the reaction occurs. Residence time, τ, is the average amount of time a discrete quantity of reagent spends inside the tank.

Assume that constant density (valid for most liquids; valid for gases only if there is no net change in the number of moles or drastic temperature change), isothermal conditions, or constant temperature (k is constant), steady state, single, irreversible reaction ($\nu_A = -1$), and first-order reaction ($r = kC_A$).

$$A \rightarrow \text{product}$$

$N_A = C_A V$ (where C_A is the concentration of species A, V is the volume of the reactor, N_A is the number of moles of species A)

$$C_A = \frac{C_{Ao}}{1 + k\tau} \qquad (2)$$

The values of the variables, outlet concentration and residence time, in Equation 2 are major design criteria. To model systems that do not obey the assumptions of constant temperature and a single reaction, additional dependent variables must be considered. If the system is considered to be in unsteady-state, a differential equation or a system of coupled differential equations must be solved. CSTR's are known to be one of the systems which exhibit complex behavior such as steady-state multiplicity, limit cycles and chaos.

In environmental engineering, a continuous or continuously stirred tank reactor (CSTR) is a system that has the following properties: there is inflow and outflow of matter, chemical reactions occur within the system's boundary, the accumulation rate of any substance, the system is in a steady-state i.e. the concentration of any substance remains constant or equivalently, the accumulation rate is zero, and any substance on the system is assumed to be homogeneously distributed

Accumulation rate = 0 = input rate - output rate + reaction rate

With the above assumptions the law of conservation of mass can be written in the generic form. [4][5]

CHAPTER 3
METHODOLOGY

This chapter discusses the project's procedure identification as well as the tools and equipment utilized throughout the course of completing this project.

3.1 Project Flow

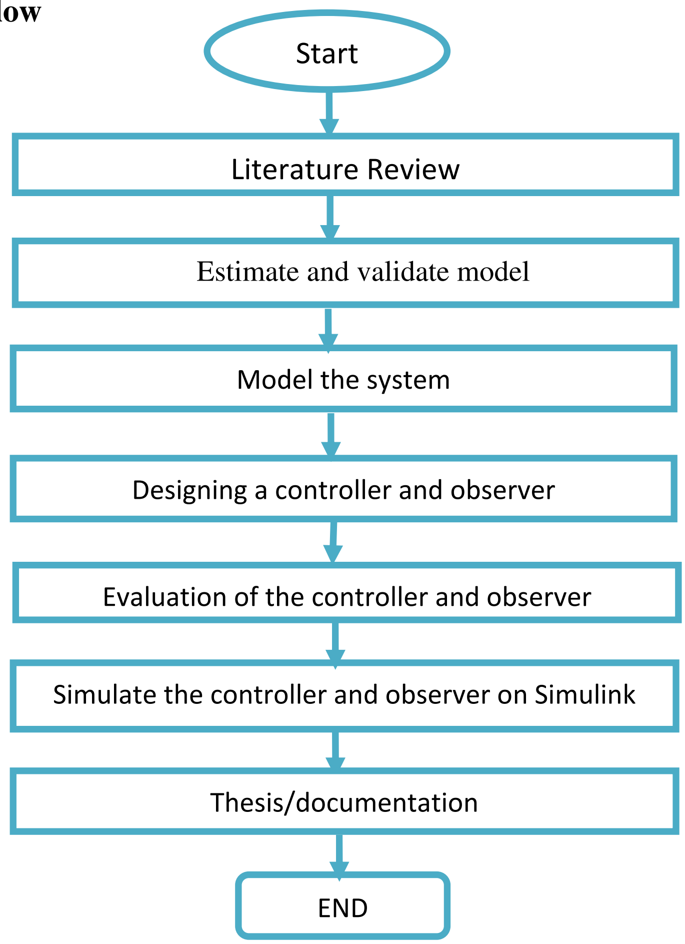

Figure 6 Project Flow

3.2 Procedures Identification

- **Phase 1**: Literature Review

  Study on the theory about the Continuous stirred tank reactor and any others related to the project.

- **Phase 2**: Estimate and validate model

  The model of the continuous stirred tank reactor is modeled via MATLAB System Identification Toolbox.

- **Phase 3:** Design controller and observers

  The controller and observer poles and gains are determined based on the model parameters

- **Phase 4**: Simulate controller and observers on SIMULINK

  The designed controller and observers are simulated on different system types on SIMULINK to observe their effects.

- **Phase 5**: Real time implementation

  By applying calculated results, which are given in the literature review to get the real plant results.

- **Phase 6** :Thesis/documentation

3.3 Tools and Equipment used

For this project I have chosen following software for the purpose of my project:

- *MATLAB*

MATLAB is a numerical computing environment and fourth generation programming language. Developed by The Math Works, MATLAB allows matrix manipulation, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs in other languages.

To use MATLAB, it is important to understand its main icons and functions. The Command Window is a tool that is used to enter data, run MATLAB functions, run M-files, and display results. It is the main menu for MATLAB. All the simulations and programming are done in M-files. M-files implements functions, or program routines, that accept input arguments and return output arguments. They operate on variables in their own workspace, separate from the MATLAB command prompt workspace.

- 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 let you design, simulate, implement, and test a variety of time-varying systems, including communications, controls, signal processing, video processing, and image processing.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter discusses the outcomes of every stage and phase of the project.

4.1 Two isothermals CSTR reactor

In an ideal steady state flow CSTR these contents in reactor are well mixed and have uniform composition throughout. Hence the outlet stream has the same composition as the fluid within the reactor. Such kind of reactor is known as mixed flow reactor. This type of set-up is used to study a non-catalytic homogeneous second order liquid phase reaction under isothermal condition. The set up consists of two feed tanks through which two reactants are fed to the reactor. The CSTR is fitted with stirrer for proper mixing. From top outlet of it samples are collected for analysis. In the following figure shown is two CSTR are connected in series.

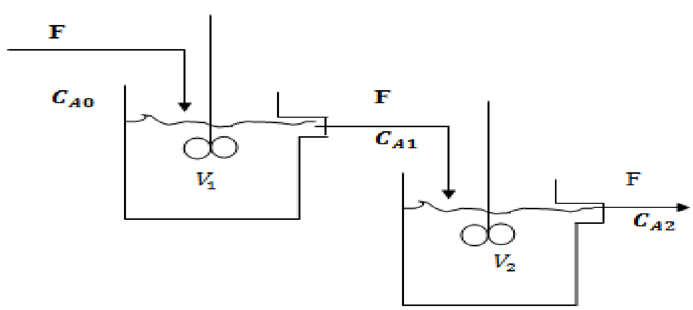

Figure 7 Two CSTR in series

4.1.1 Data

The given data is as below; the two systems are the liquid in each tank

- V_1=V_2=1.05m^3, F=0.085m^3/min;
- $(C_{A0})_{init}$=0.925 moles/m^3
- The chemical reaction is first-order, r_A=-kC_A with k=0.040min^{-1}.
- The reactor is well mixed and isothermal.

4.1.2 Formulation

Consider two isothermal continuous stirred-tank reactors (CSTRs) with a recycle stream on which a first-order reaction is occurring. The governing equations of the system are,

First tank: $$V_1 \frac{dC_{A1}}{dt} = F(C_{A0} - C_{A1}) - V_1 k C_{A1} \qquad (3)$$

Second tank: $$V_2 \frac{dC_{A2}}{dt} = F(C_{A1} - C_{A2}) - V_2 k C_{A2} \qquad (4)$$

Now, solving by above two equations and then by writing them in the form of state-space.

$$V_1 \frac{dC_{A1}}{dt} = FC_{A0} - FC_{A1} - V_1 k C_{A1} \qquad (5)$$

$$V_2 \frac{dC_{A2}}{dt} = FC_{A1} - FC_{A2} - V_2 k C_{A2} \qquad (6)$$

$$\frac{dC_{A1}}{dt}=\frac{F}{V_1}C_{A0}-\frac{F}{V_1}C_{A1}-kC_{A1} \tag{7}$$

$$\frac{dC_{A2}}{dt}=\frac{F}{V_2}C_{A1}-\frac{F}{V_2}C_{A2}-kC_{A2} \tag{8}$$

This equation for tank: 1

$$\frac{dC_{A1}}{dt}=\frac{F}{V_1}C_{A0}-(\frac{F}{V_1}+k)C_{A1} \tag{9}$$

And following equation for tank: 2

$$\frac{dC_{A2}}{dt}=\frac{F}{V_2}C_{A1}-(\frac{F}{V_2}+k)C_{A2} \tag{10}$$

Now, by further solving these equations in the form of state -space and the following are the state-space equations.

$$\dot{\mathbf{x}}(t) = A(t)\mathbf{x}(t) + B(t)\mathbf{u}(t)$$
$$\mathbf{y}(t) = C(t)\mathbf{x}(t) + D(t)\mathbf{u}(t)$$

We write the above equation (9) and (10) in the form state-space. First of all we take the state vector equation by writing it in the matrix form,

$$\dot{\mathbf{x}}(t) = A(t)\mathbf{x}(t) + B(t)\mathbf{u}(t)$$

$$\begin{bmatrix} \frac{dC_{A1}}{dt} \\ \frac{dC_{A2}}{dt} \end{bmatrix}=\begin{bmatrix} -(\frac{F}{V_1}+k) & 0 \\ \frac{F}{V_2} & -(\frac{F}{V_2}+k) \end{bmatrix}\begin{bmatrix} C_{A1} \\ C_{A2} \end{bmatrix}+\begin{bmatrix} \frac{F}{V_1} \\ 0 \end{bmatrix}C_{A0}$$

And second is output equation, in this we assume the vector C (t) = $[1 \quad 0]$, and D (t) =0, by assuming these values, we write in the form of matrix,

$$\mathbf{y}(t) = C(t)\mathbf{x}(t) + D(t)\mathbf{u}(t)$$

$$T=\begin{bmatrix} 0 & 1 \end{bmatrix}\begin{bmatrix} C_{A1} \\ C_{A2} \end{bmatrix}+0,$$

Now we will put the data in the matrix form for further solution as we have given above, to get the further simplification.

$$\begin{bmatrix} \frac{dC_{A1}}{dt} \\ \frac{dC_{A2}}{dt} \end{bmatrix}=\begin{bmatrix} -(\frac{0.085}{1.05}+0.040) & 0 \\ \frac{0.085}{1.05} & -(\frac{0.085}{1.05}+0.040) \end{bmatrix}\begin{bmatrix} C_{A1} \\ C_{A2} \end{bmatrix}+\begin{bmatrix} \frac{0.085}{1.05} \\ 0 \end{bmatrix}0.925$$

For further simplification, we solve the above matrix

$$\begin{bmatrix} \frac{dC_{A1}}{dt} \\ \frac{dC_{A2}}{dt} \end{bmatrix}=\begin{bmatrix} -0.120952381 & 0 \\ 0.08095238 & -0.120952381 \end{bmatrix}\begin{bmatrix} C_{A1} \\ C_{A2} \end{bmatrix}+\begin{bmatrix} 0.08095238 \\ 0 \end{bmatrix}0.925$$

$$Y\ (t)=\begin{bmatrix} 0 & 1 \end{bmatrix}\begin{bmatrix} C_{A1} \\ C_{A2} \end{bmatrix}+0,$$

In order to get the result we apply above given data, after implementing them the result is taken in the form of state-space representation. We knew the terms have been used in the above representation and it is taken via state-space approach, for further simplification in order to get the concentration graphs with respect to time. Hence we have to find the transfer function of the system. Following formula is to take the transfer function.

$$G(s) = C(SI-A)^{-1}B$$

$$A=\begin{bmatrix} -0.120952381 & 0 \\ 0.08095238 & -0.120952381 \end{bmatrix}$$

$$B=\begin{bmatrix} 0.08095238 \\ 0 \end{bmatrix} \quad \text{And } C=\begin{bmatrix} 0 & 1 \end{bmatrix}, \ SI=\begin{bmatrix} S & 0 \\ 0 & S \end{bmatrix}$$

All data is given so by putting the values inside above equation. We have got following result.

$$G(s) = \frac{0.006553}{s^2 + 0.241905s + 0.01463}$$

The above transfer function is for CSTR system. Here in this project we are considering the concentration of liquid in tank2.

4.2 Simulation of the system

In order to create the simulation diagram of the system we should know the all data which is going to implement in the system and the all data is given in the form of state-space. To design a system in the Simulink in which we will provide step input to the system and all gains will be connected and after that to see the output we will connect scope. Hence we are creating a Simulink to check the behavior of concentration versus time.

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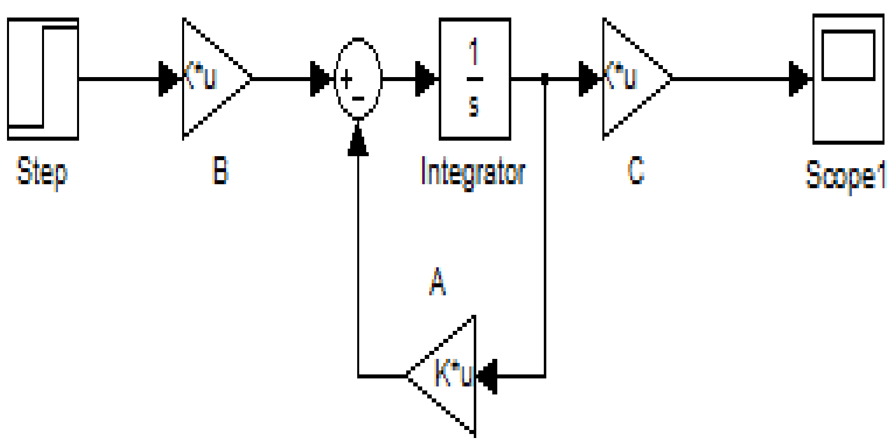

Figure 8 Block diagram of the system

Following figures are showing the input response and output response of the simple system.

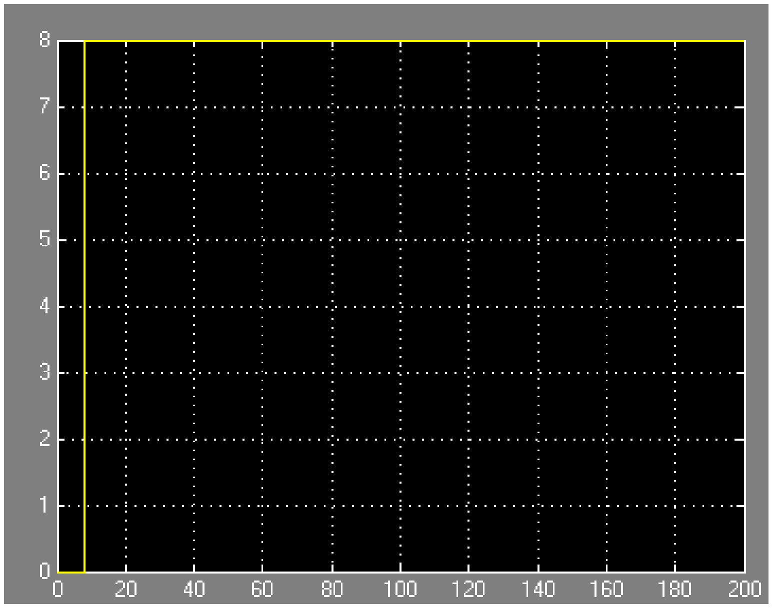

Figure 9 Step input

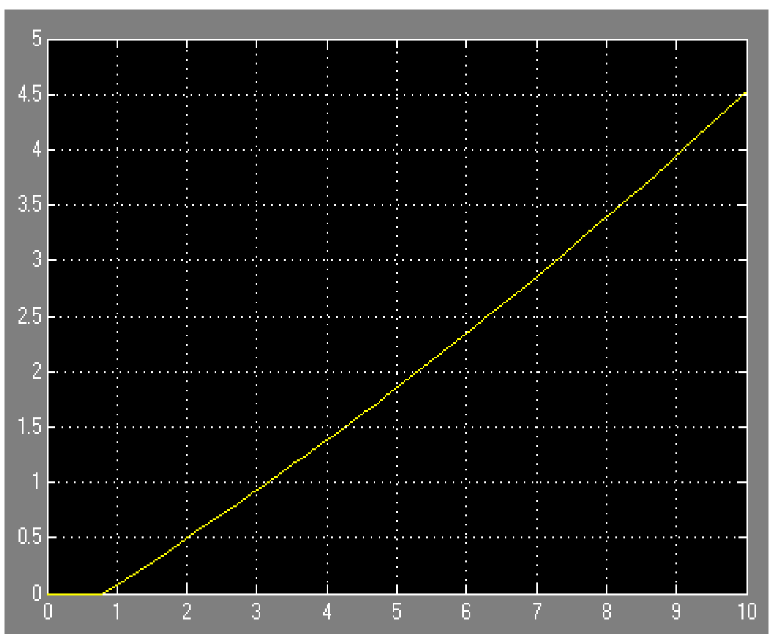

Figure 10 The output response of the state-space system when a step input is applied

The above graph shows the output response of the state-space system when a step input is applied and it gives the graph time versus concentration of fluid in tank2. When we apply the input to the system the concentration is linearly increasing with respect to time and it has no overshoot, no settling time and rise time of the response is 0.99sec. Before designing a feedback controller we have to find out the two main conditions. The conditions are controllability and observability.

Controllability and observability are dual aspects of the same problem. The concepts of controllability and observability are very similar. In fact, there is a concrete relationship between the two. We can say that a system (A, B) is controllable if and only if the system (A', B, B', D) is observable. This fact can be proven by plugging A' in for A, and B' in for C into the observability gramian. The resulting equation will exactly mirror the formula for the controllability gramian, implying that the two results are the same. [6]

4.3 Controllability

In the world of control engineering, there are a slew of systems available that need to be controlled. The task of a control engineer is to design controller and compensator units to interact with these pre-existing systems. However, some systems simply cannot be controlled (or, more often, cannot be controlled in specific ways). The concept of controllability refers to the ability of a controller to arbitrarily alter the functionality of the system plant.

Controllability play important role in the design of control systems in state space. The conditions of controllability may govern the existence of complete solution to the control system design problems. The solution to this problem may not exist if the system considered is not controllable. Thus before proceed to the modeling and simulations, controllability of this system are determined.

We have given the matrix A and B as below,

$$A=\begin{bmatrix} -0.120952381 & 0 \\ 0.08095230 & -0.120952381 \end{bmatrix}, \qquad B=\begin{bmatrix} 0.08065238 \\ 0 \end{bmatrix}$$

$C = [0 \quad 1]$, by finding the controllability

$$AB=\begin{bmatrix} -0.009755097 \\ 0.00653 \end{bmatrix}, \qquad M_c=[B \quad AB]=\begin{bmatrix} 0.08095238 & -0.009755097 \\ 0 & 0.00653 \end{bmatrix}$$

$$\det\begin{bmatrix} 0.08095238 & -0.009755097 \\ 0 & 0.00653 \end{bmatrix}=0.005286190414\neq 0$$

Thus, the system is controllable.

4.4 Observability

A system with an initial state, $x(t_0)$ is observable if and only if the value of the initial state can be determined from the system output y(t) that has been observed through the time interval $t_0 < t < t_f$. If the initial state cannot be so determined, the system is unobservable. [6]

Observability plays an important role in the design of control systems in state space. The condition observability may govern the existence of complete solution to the control system design problems. The solution to this problem may not exist if the system considered is not controllable. Thus before proceed to the modeling and simulation, observability of this system is determined.

$$A=\begin{bmatrix} -0.120952381 & 0 \\ 0.08095238 & -0.120952381 \end{bmatrix}, \qquad C=[0 \quad 1]$$

$[C^T \quad A^T C^T]$, to solve that $\quad C^T=\begin{bmatrix} 0 \\ 1 \end{bmatrix}, \quad A^T=\begin{bmatrix} -0.120952381 & 0.08095238 \\ 0 & -0.120952381 \end{bmatrix}$,

$$A^T C^T=\begin{bmatrix} -0.120952381 & 0.08095238 \\ 0 & -0.120952381 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \end{bmatrix}=\begin{bmatrix} 0.08095238 \\ -0.120952381 \end{bmatrix}$$

$$[C^T \quad A^T C^T]=\begin{bmatrix} 0 & 0.08095238 \\ 1 & -0.120952381 \end{bmatrix}$$

$$\det[C^T \quad A^T C^T] \Rightarrow \det\begin{bmatrix} 0 & 0.08095238 \\ 1 & -0.120952381 \end{bmatrix} = -0.08095238 \neq 0$$

Thus, the system is observable.

In order to design a observer hence the system should be observable and to find desirable response

From the above calculation we observed that the system is found to be controllable and observable.

Overall, it is a nonlinear Continuous stirred tank reactor (CSTR) and now we will develop the some results of the simulation is obtained yet until the Simulink modeling finishes. We knew that the system is controllable and observable. To develop a controller we need to find the feed forward gain and feedback gain of the system. It is necessary to reduce the transient period associated with start-up and shut-down is crucial for improving plant productivity performance, including manpower saving and efficient energy. Hence it will be very important to develop a versatile controller optimizing the transient as well as the steady-state operations.

4.5 Feedback controller

Feedback is extensively used in control theory, using a variety of methods including state space (controls), full state feedback (also known as pole placement). A controller is a device which monitors and affects the operational conditions of a given dynamical system. Control systems are what make machines, in the broadest sense of the term, function as intended. Control systems are most often based on the principle of feedback, whereby the signal to be controlled is compared to a desired reference signal and the discrepancy used to compute corrective control action. For this reason it is important that a theory of feedback not only lead to good designs when these are possible, but also indicate directly and unambiguously when the performance objectives cannot be met. A feedback control system is valuable because it provides the engineer with the ability to adjust the transient response. In addition the sensitivity of the system and the effect of disturbance can reduced significantly.

The following parameters are needed to design a controller.

4.4.1 Controller feedback gain K

4.4.2 Controller forward gain N

4.5.1 Controller feedback gain K

A controller can be designed to specifications only if the system is controllable. The reason for adding feedback is to improve the system characteristics or transient response such as rise-time, overshoot, settling time. Systems For the linear system with the state-space representation, the state feedback controller is of the form, u = -Kx + Nv.

$$A=\begin{bmatrix} -0.120952381 & 0 \\ 0.08095238 & -0.120952381 \end{bmatrix} \quad B=\begin{bmatrix} 0.08065238 \\ 0 \end{bmatrix} C = \begin{bmatrix} 0 & 1 \end{bmatrix},$$

Hence we have found the system controllable.

$$M_c=|B \quad AB| = \begin{bmatrix} 0.08095238 & -0.009755097 \\ 0 & 0.00653 \end{bmatrix} \# 0$$

So the system is controllable, now to find the controller feedback gains K by using the Ackerman's method. First of all we need to find the inverse of the M_c and then by putting the values in the Formulas which is given below. k=q_I α_c (A), q_I is the last row of M_c inverse.

$$M_c^{-1}= \frac{Adj\ M_c}{det M_c} = \begin{bmatrix} 12.3 & 0 \\ 18.454 & 153.1401633 \end{bmatrix}$$

$$q_I = [18.454 \quad 153.1401633]$$

Now assuming the poles of the closed loop system are at -1.7, -0.1

α_c (s)=s^2+1.8s+0.17, α_c (A)= A^2+1.8A+0.17I, by solving it. We got below result.

α_c (A)=$\begin{bmatrix} -0.0333084285 & 0 \\ 0.126131284 & -0.0333084285 \end{bmatrix}$, Now to get the value of K

K= q_I α_c (A) = $[18.454 \quad 153.1401633]\begin{bmatrix} -0.0333084285 & 0 \\ 0.126131284 & -0.0333084285 \end{bmatrix}$

K=$[18.7011 \quad 5.10083]$

4.4.2 Controller forward gain N

We use the following method to find the controller forward gain N.

N=N_U +kN_X , $\begin{bmatrix} A & B \\ C & D \end{bmatrix}\begin{bmatrix} N_X \\ N_U \end{bmatrix}=\begin{bmatrix} 0 \\ I \end{bmatrix}$, $\begin{bmatrix} N_X \\ N_U \end{bmatrix}=\begin{bmatrix} A & B \\ C & D \end{bmatrix}^{-1}\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$

$$\begin{bmatrix} N_X \\ N_U \end{bmatrix}=\begin{bmatrix} -0.120952381 & 0 & 1 \\ 0.08095238 & -0.120952381 & 0 \\ 0 & 1 & 0 \end{bmatrix}^{-1}\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$\begin{bmatrix} N_X \\ N_U \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 \\ -12.3529 & 0 & 0 \\ 0 & -1 & 0 \end{bmatrix}\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$ $\quad N_X=\begin{bmatrix} 1 \\ 0 \end{bmatrix}$ $\quad N_U=0$

N=N_U +kN_X $\quad$ K=$[18.7011 \quad 5.10083]$

N=18.7011

The first step of the design involves determining the state feedback gain k to shape the transient response, by solving the regulator problem. The next step is to design the forward gain (N). And the final step is to simulate the system and to get the expected response. The following figure 10 shows the feedback controller block diagram.

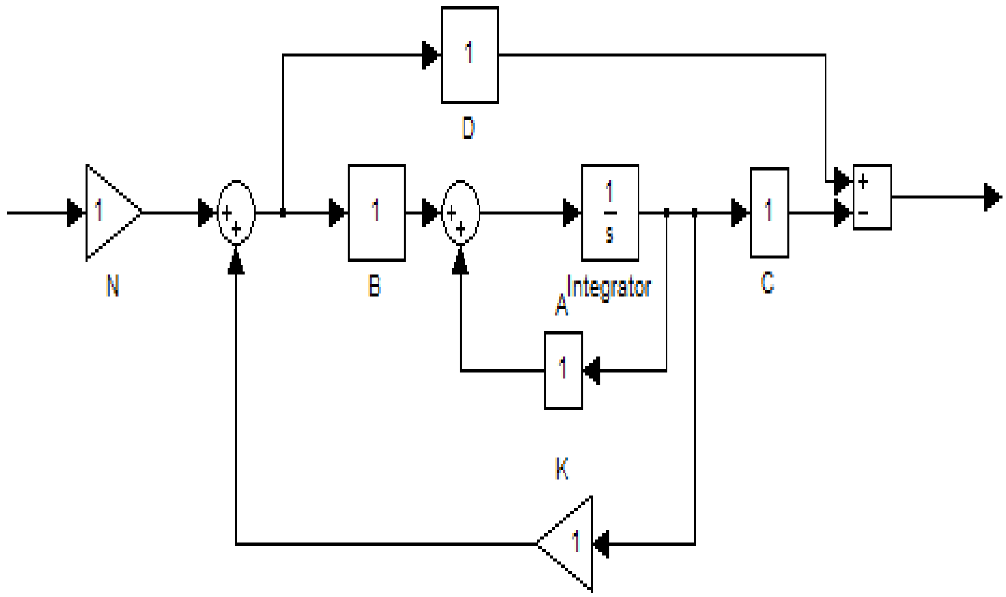

Figure 11 Feedback controller block diagram

The feedback controller system is created and designed in a Simulink. In the **figure 12** we have our system block, forward gain (gain 2), feedback gain (gain1, gain), step input and scope for the output. The reason for designing a feedback controller is to now we will apply the step input to the system to get the response with and without the forward gain (gain2).

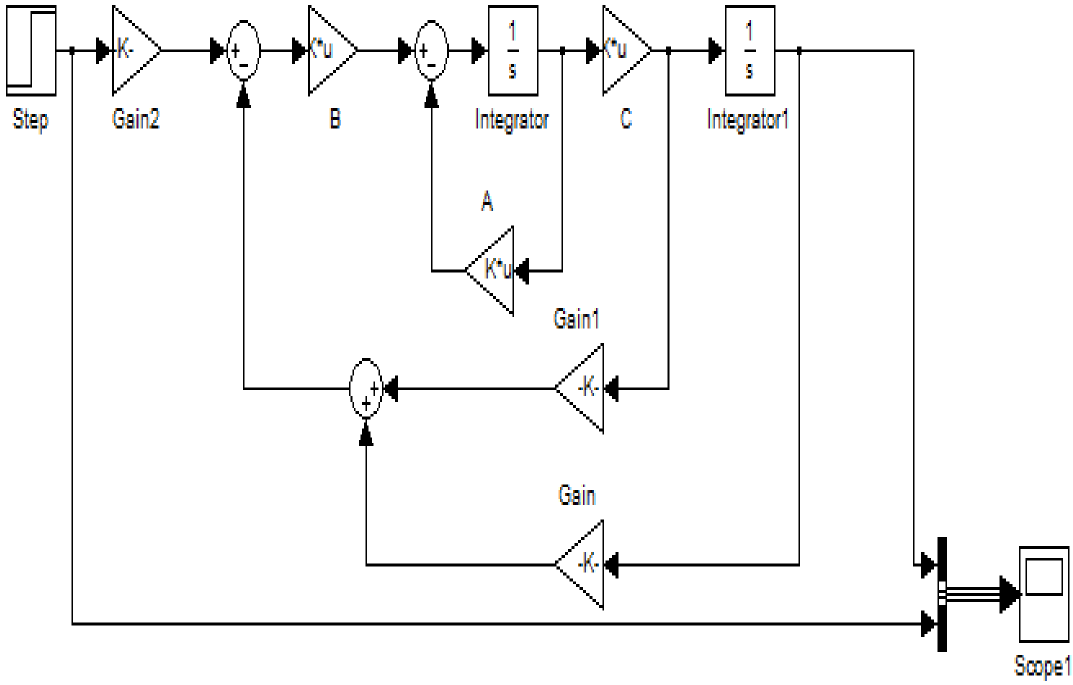

Figure 12 Simulink diagram of the system with feed forward gain

The following figures 13a and 13b shows the result of the feedback controller with forward gain.

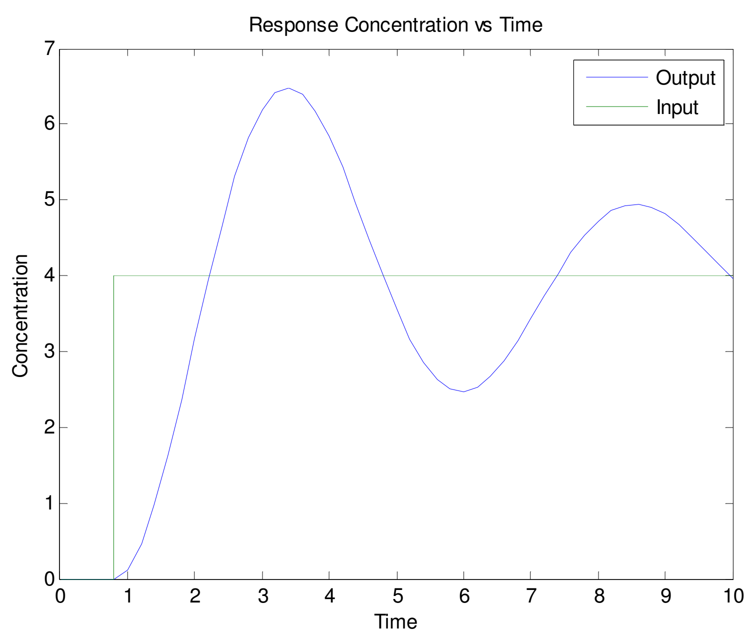

Figure 13a The output response of the system with the forward gain (gain2)

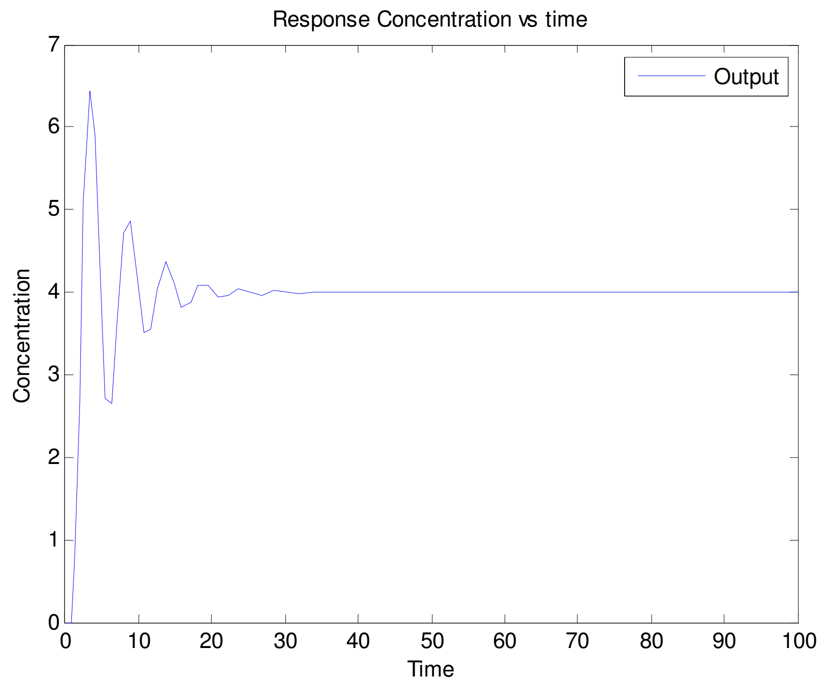

Figure 13b The output response of the system with the forward gain (gain2)

The result is without feed forward gain.

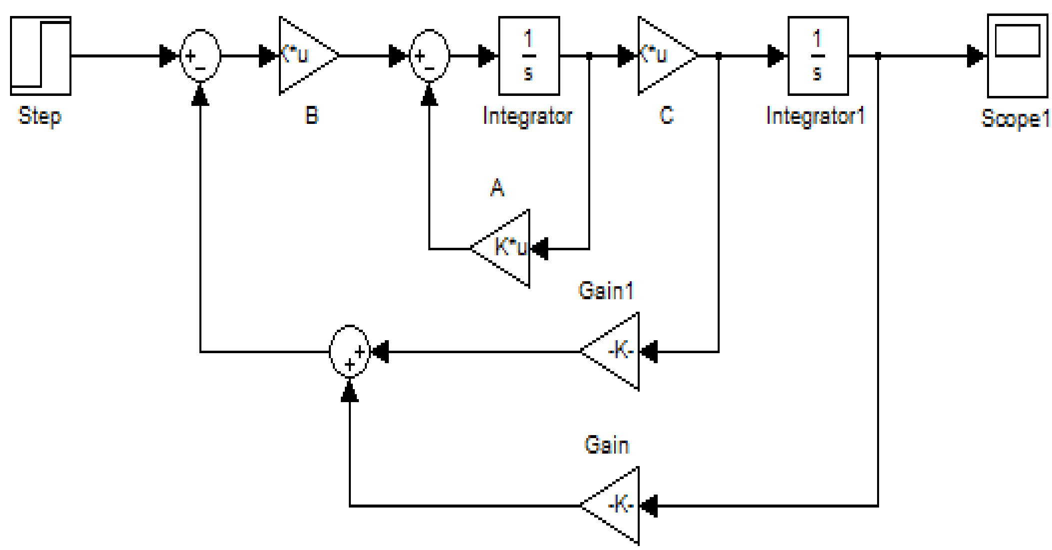

Figure 14 Simulink diagram of the system without feed forward gain

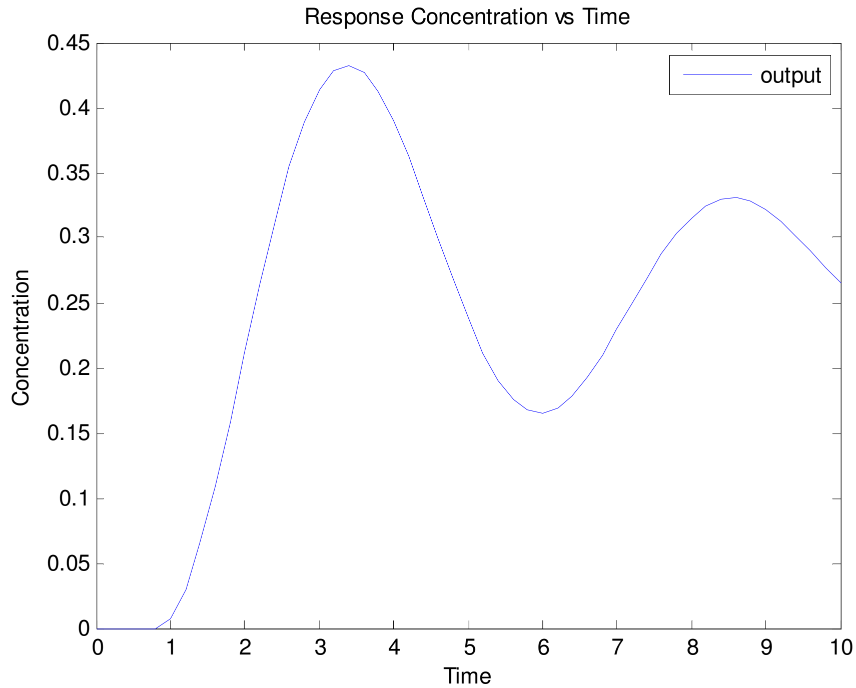

Figure 15a The output response of the system without the forward gain (gain2).

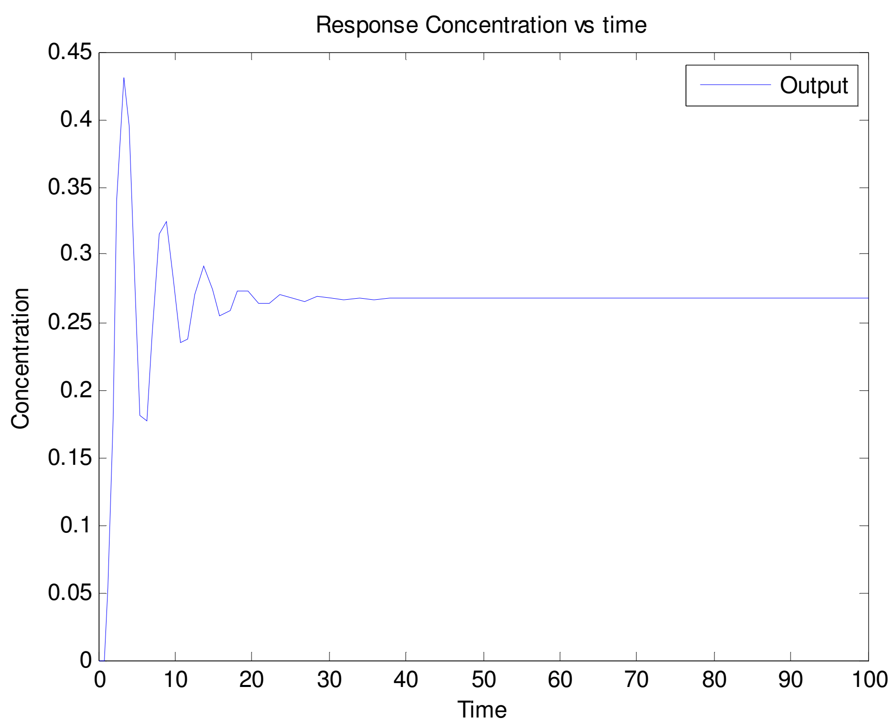

Figure 15b The output response of the system without the forward gain (gain2).

Hence the above behavior of the system is without the feed forward gain by applying the step input.

In this feedback controller, the desired poles are -1.7 and -0.1. One pole is located near to the *jw-axis and* other one far from it on the left hand plane. Figure 13a and 13b shows the without forward gain and Figure 15a and 15b shows with forward gain. When it is without forward gain the response is less amplified and less value but there is also some overshoot and settling time and also its getting stable after some time and when forward gain is included to the system response became more amplified and but there is still some overshoot and settling time in the response. Hence the result is expected result and its becoming stable after the passage of time.

4.6 Feedback tracking controller

Simulation studies show the effectiveness of the present design method of digital tracking controller for a nonlinear CSTR with time-delay. Modeling and simulation for the tracking controller to track the varying reference signal contains an integrating element.

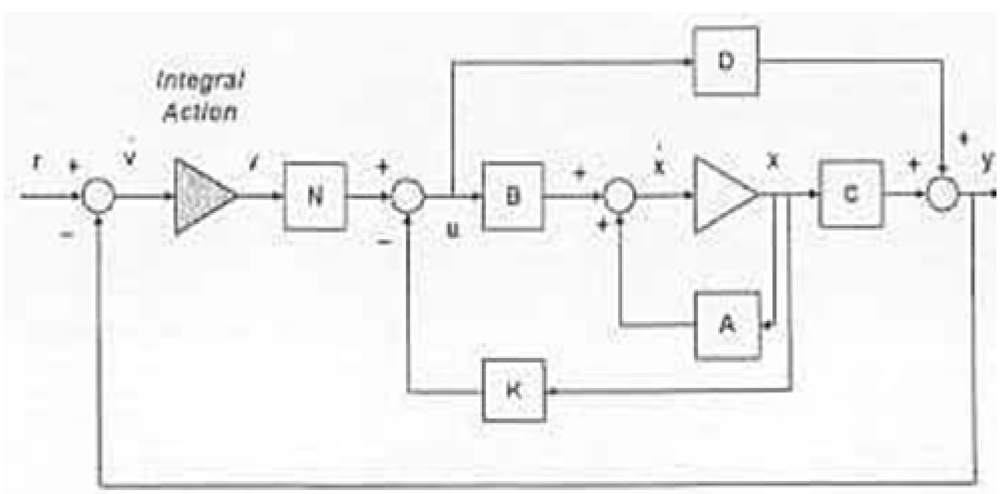

Figure 16 Feedback tracking controller block diagram

The closed loop equation involving the complete set of states are given by.

$$\begin{bmatrix} \dot{x} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} (A - BK) & BN \\ -C & 0 \end{bmatrix} \begin{bmatrix} x \\ v \end{bmatrix} + \begin{bmatrix} B \\ -D \end{bmatrix} u + \begin{bmatrix} 0 \\ 1 \end{bmatrix} r$$

$$A = \begin{bmatrix} (A - BK) & BN \\ -C & 0 \end{bmatrix}$$

The tracking error dynamics will be governed by the eigenvalues for the closed loop system, the pole placement method can be used to determine the gains. A SIMULINK diagram for the system was created where the model in Modeling and Simulation. A unit step and then a continuous (sinusoidal) and also ramp input were applied to the system and the output response was obtained as shown in the figures below.

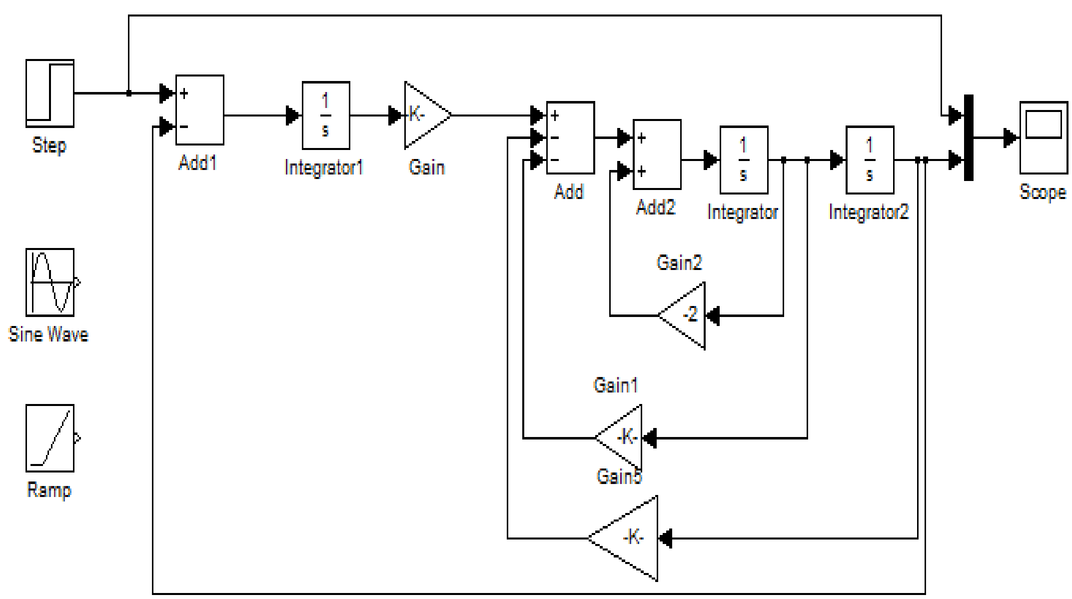

Figure 17: The block diagram of the system

The following results of the feedback tracking controller when we applied various kind inputs to the system.

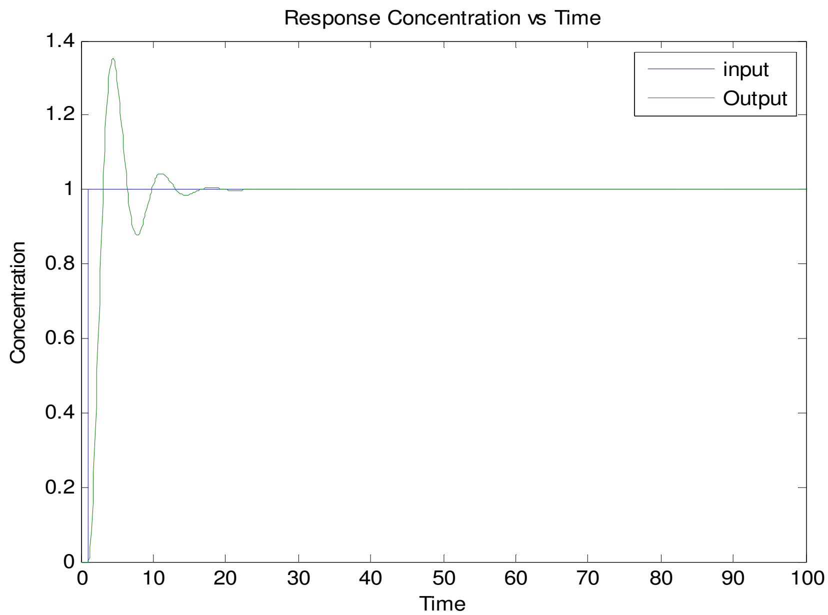

Figure 18: The output response of the system compared to step input

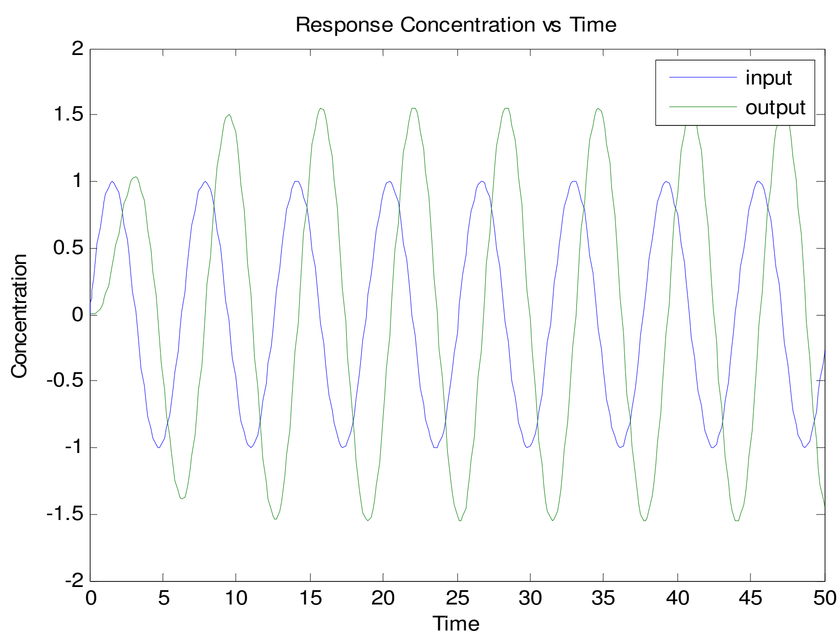

Figure 19a: The output response of the system compared to sinusoidal input at frequency of 1rad/sec.

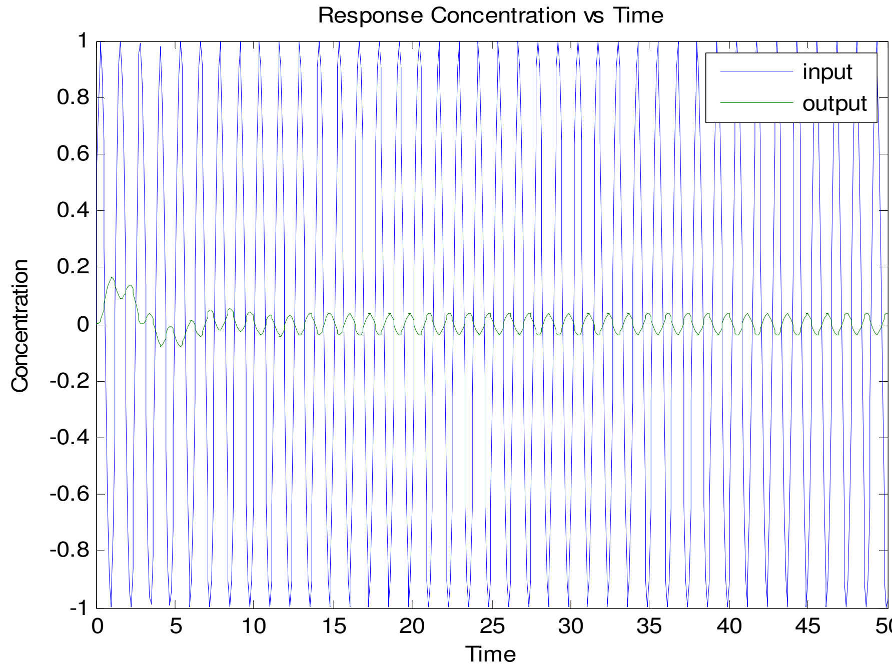

Figure 19b: The output response of the system compared to sinusoidal input at frequency of 5rad/sec.

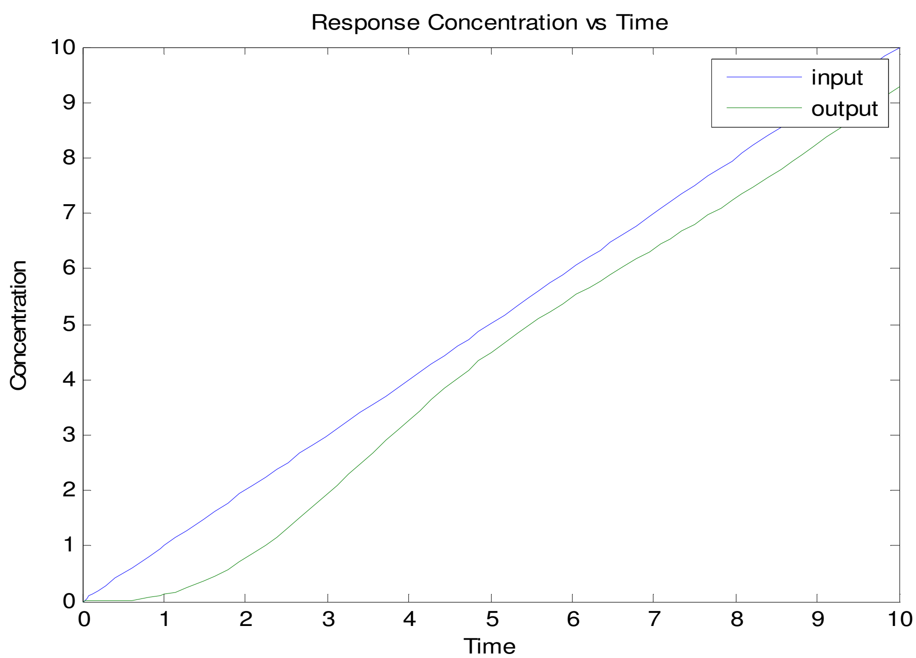

Figure 20: The output response of the system compared to ramp input

Referring to above graphs, the input is indicated the blue line whereas the output of the system is indicated by the red line. Theoretically, the output response of the system should resemble the applied input. However, for both graphs, the output dose not resembles the input. The difference in graph can be caused by many factors such as: disturbance and noise in the system

The bandwidth of the system increase as the selected desired poles are further onto the left hand side of the plane. This causes the system to be more sensitive to noise and disturbance that is likely to alter the output response of the system.

4.7 Full state Observer

In modern control theory, a state observer is a system that models a real system in order to provide an estimate of its internal state, given measurements of the input and output of the real system. Here we will design an observer for continuous stirred tank reactor and then we simulate in the Simulink to check the response of CSTR.

$$\begin{bmatrix} \frac{dC_{A1}}{dt} \\ \frac{dC_{A2}}{dt} \end{bmatrix} = \begin{bmatrix} -0.120952381 & 0 \\ 0.08095238 & -0.120952381 \end{bmatrix}, \begin{bmatrix} C_{A1} \\ C_{A2} \end{bmatrix} + \begin{bmatrix} 0.08095238 \\ 0 \end{bmatrix} 0.925$$

$$T = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} C_{A1} \\ C_{A2} \end{bmatrix} + 0,$$

Now we assume the poles, both are left sided poles and one is nearer and other pole is far from origin -1.8, -0.2.

$$A = \begin{bmatrix} -0.120952381 & 0 \\ 0.08095238 & -0.120952381 \end{bmatrix}, \quad L = \begin{bmatrix} l_1 \\ l_2 \end{bmatrix} \text{ and } \quad C = \begin{bmatrix} 0 & 1 \end{bmatrix}$$

Formula $[\lambda I - (A - LC)] = 0$, First of all we find the (A-LC).

$$A\text{-}LC = \begin{bmatrix} -0.120952381 & 0 \\ 0.08095238 & -0.120952381 \end{bmatrix} - \begin{bmatrix} l_1 \\ l_2 \end{bmatrix} \begin{bmatrix} 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} \lambda & 0 \\ 0 & \lambda \end{bmatrix} - \begin{vmatrix} -0.120952381 & -l_1 \\ 0.08095238 & -0.120952381 - l_2 \end{vmatrix} = 0$$

$$\lambda^2 - \lambda\,(l_1 + 0.2419047) + (0.08095238 l_1 + 0.120952381 l_2 + 0.01463) = 0 \quad (11)$$

Now by taking the poles, -1.8, -0.2.

$$(\lambda - 1.8)(\lambda - 0.2) = 0 \text{ and } \lambda^2 - 0.2\,\lambda - 1.8\,\lambda + 0.36 = 0$$

$$\lambda^2 - 2\lambda + 0.36 = 0 \qquad \textbf{(12)}$$

From equation (11) by taking the middle part of the equation and making equal with middle part of equation (12). And also can be considered last parts of both equations. But here we consider last part.

$$l_2+0.2419047=-2$$

$$l_1 0.08095238 + 0.12095238 l_2 + 0.01463=0.36$$

$$l_1=1.278113, \quad l_2=-2.2419047$$

$$L=\begin{bmatrix} 1.278113 \\ -2.2419047 \end{bmatrix} \qquad A\text{-}LC=\begin{bmatrix} -0.120952381 & -1.278113 \\ 0.08095238 & 2.12095232 \end{bmatrix}$$

Now further step is to design and simulate the observer. The following figure is the design of observer by using the Simulink.

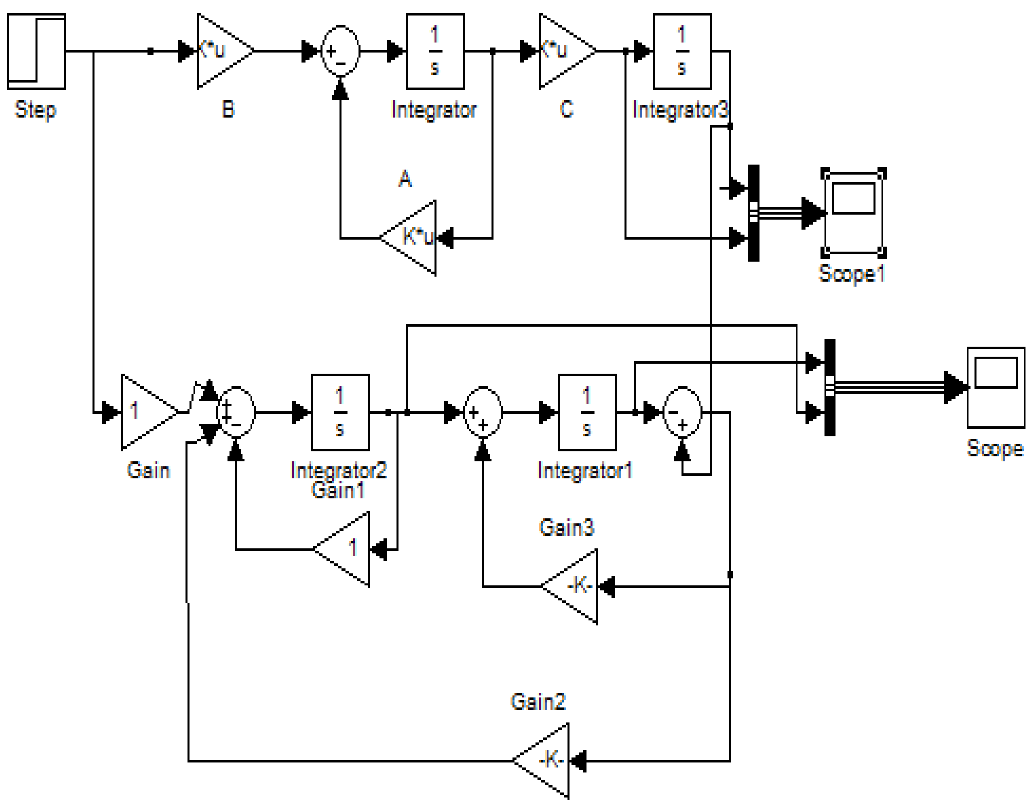

Figure 21 Full-state observers in Simulink

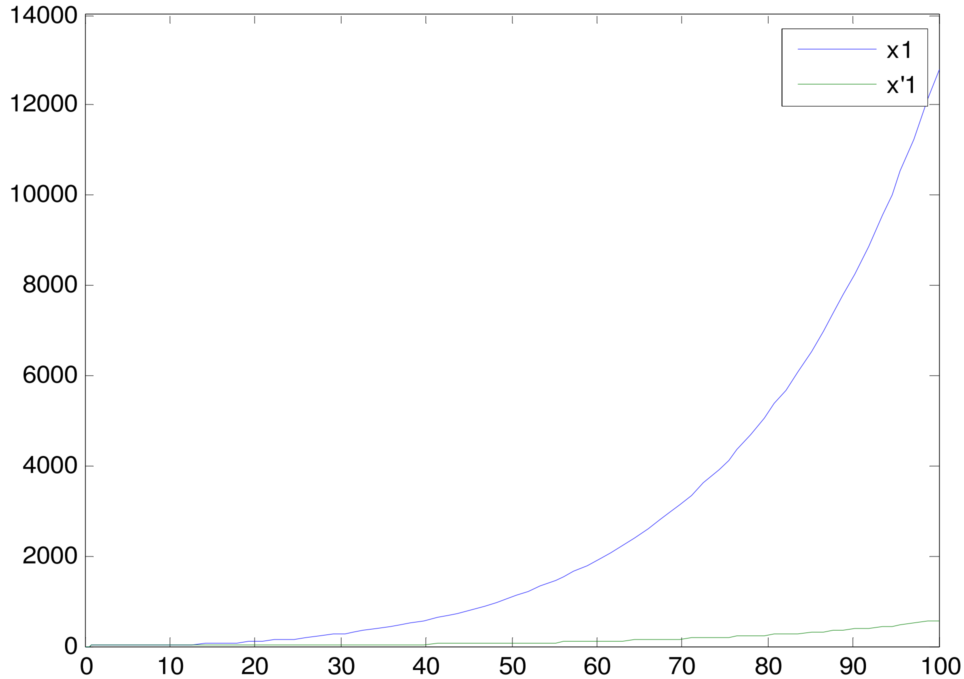

Figure 22 Full-state observer's response at scope 1(actual state)

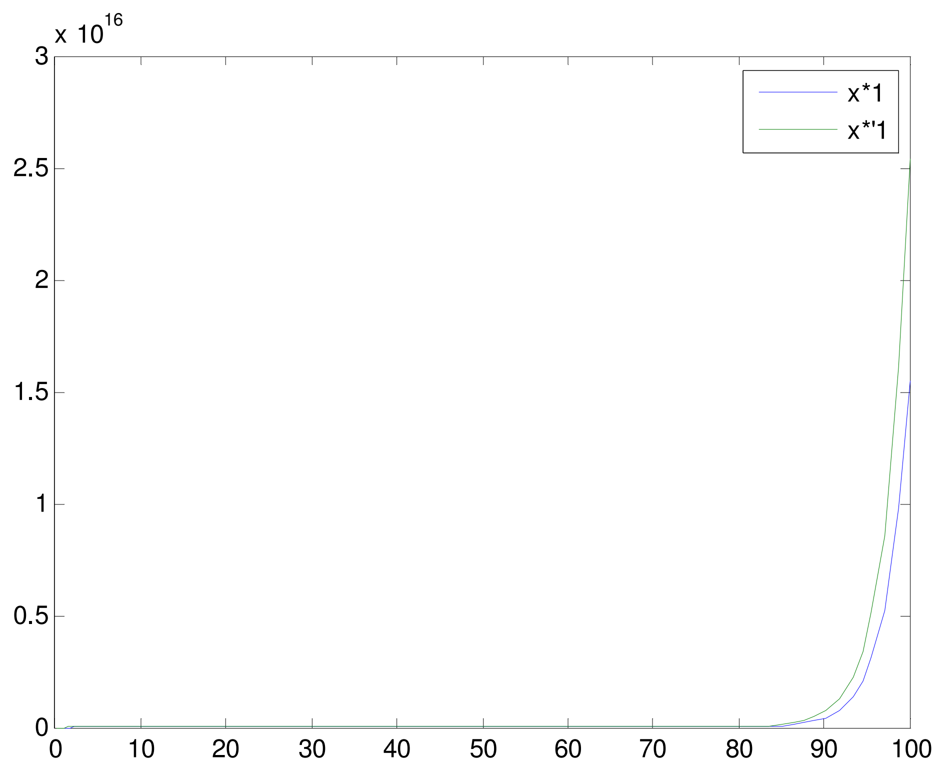

Figure 23 Full-state observer's response at scope (estimated state)

Full- state observer is shown in figure 22 and it is built in the Simulink/MATLAB diagram of the system to check the behavior of concentration versus time. In above graph red color shows the input and yellow color showing the output of the system.

4.7.1 Full state observer with feedback gains

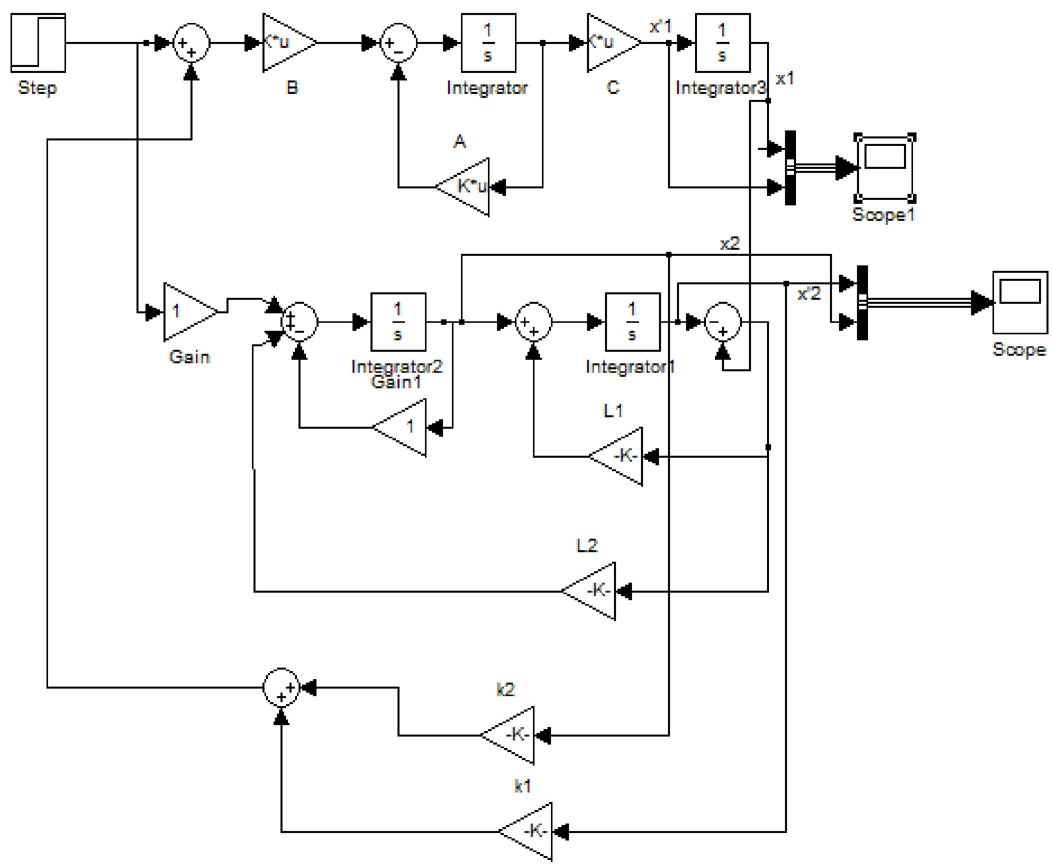

Figure 24 Full-state observer with feedback gains in Simulink

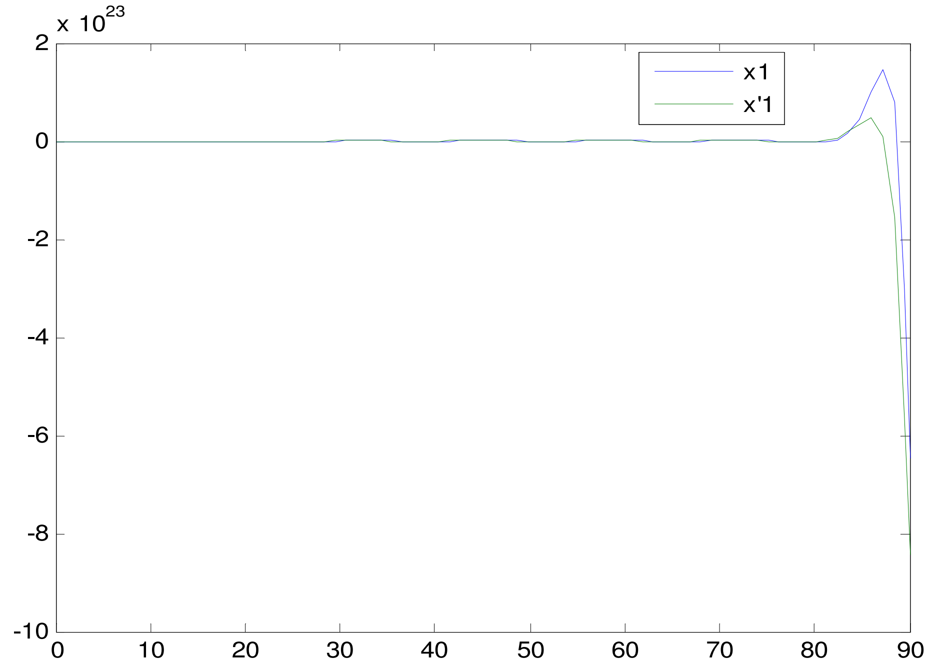

Figure 25 Full-state observer's response at scope 1(actual state)

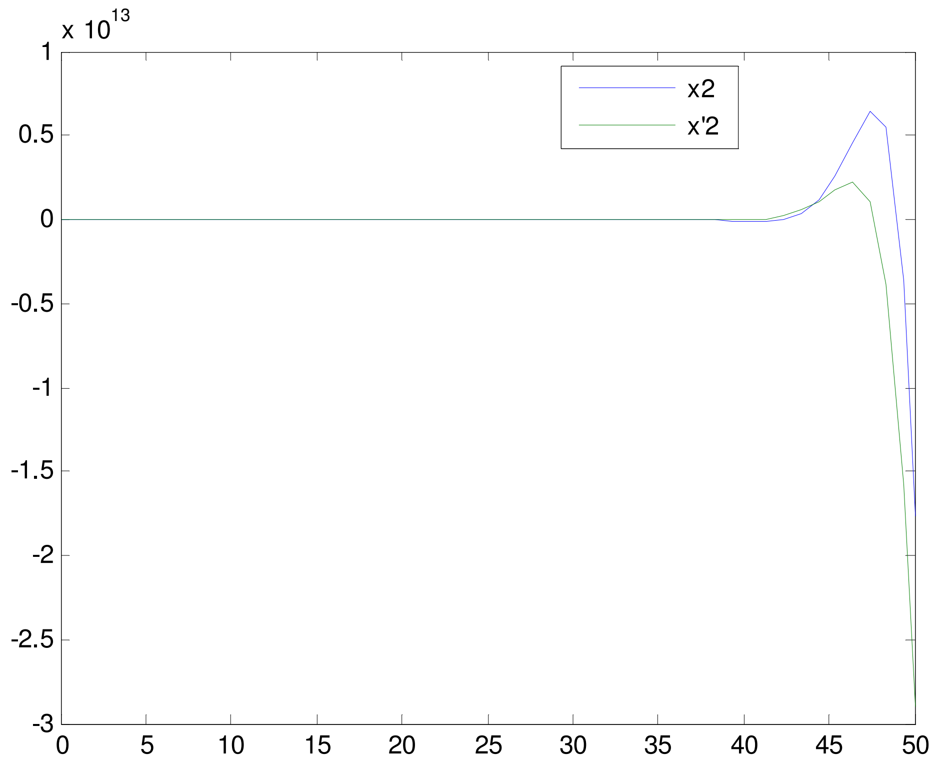

Figure 26 Full-state observer's response at scope (estimated state)

CHAPTER 5

CONCLUSION AND RECOMMENDATION

This chapter includes the entire project and proposes several recommendations, which could improve the outcomes of the project

5.1 Conclusion

In this project the author went through organized set of stages to reach his desired results starting from Simulink modeling and sampling. The continuous stirred tank reactor is an important process used in many applications. It has widespread application in industry and embodies many features of other types of reactors. The advantages of the Continuous stirred tank reactor, it has continuous operation, good temperature control, easily adapts to two phase runs, simplicity of construction , low operating cost and finally it is easy to clean. Details study on the process in particular modeling and analysis of the system that will enhance the understanding on way to improve the control strategies on the continuous stirred tank reactor process “CSTR”.A continuous stirred tank reactor (CSTR) was successfully modeled on Simulink from the theoretically calculated data, producing simulated responses that actual ones. Controller and observer were effectively designed using pole placement method, producing promising results that indicate the practically of modern control in plant process control systems. The conclusion, with the accomplishment of theoretically implementing the concept of modern control engineering in plant process control systems.

5.2 Recommendation

Implement controller and observers on actual plant: the promising results from the simulations point only to one direction and implement the controller and observer on actual plant to see its effectiveness as an alternative control strategy.

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APPENDICES

APPENDIX A

PROJECT GANTT CHART

NO	Detail/week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Project Work Continue														
2	Submission of progress Report 1														
3	Project Work Continue														
4	Submission of progress Report 2														
5	Project Work Continue														
6	Draft Report														
7	Final report														
8	Technical Report														