PROCESS FAULT ANALYSIS USING DIGRAPH METHOD

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF:

Bachelor of Technology

In

Chemical Engineering

By

KREETI DAS

Department of Chemical Engineering

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Under the Guidance of**:**

Dr. Madhusree Kundu

Department of Chemical Engineering

National Institute of Technology, Rourkela

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Rourkela

<u>CERTIFICATE</u>

This is to certify that the thesis entitled, “Process Fault Analysis using Digraph Method” submitted by Miss Kreeti Das in partial fulfilment of the requirements for the award of Bachelor of Technology in Chemical Engineering at the National Institute of Technology, Rourkela is an authentic work carried out by her under my supervision and guidance.

To the best of my knowledge, the matter embodied in this thesis has not been submitted to any other University / Institute for the award of any degree or diploma.

Date:

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And I would like to convey my appreciation to all those who directly or indirectly supported me in carrying out this thesis work successfully.

Kreeti Das

ABSTRACT

Fault detection in chemical processes and their isolation is becoming a pressing demand due to rising concerns regarding safety. An undetected fault can often get out of control and cause massive losses to an industry in terms of infrastructure and personnel. . When a fault is detected the next steps comprise of identifying the root of the fault, determining the extent to which the system functioning can be maintained despite the fault and to find a repair or solution to the fault. Traditional methods of fault diagnosis include real time analysis of faults or/and sequential testing procedures but none guarantee an early detection; thus confusion is inevitable in case of multiple faults. Due to these limitations, the digraph method of fault detection has been an area of interest lately. The foundations of this method are developed based on human reasoning and analytical skills and later the prepared model is validated with the help of simulation. The advantages of this method being the relative simplicity of the model to be referred in the case of a fault and the fast diagnosis of root of fault; this process has been applied to three processes in this paper and its effectiveness observed.

The three processes that have been studied are: Jacketed Continuous Stirred Tank Reactor, Binary Distillation Column and Drum Boiler. Mechanism of each process was studied in detail; their mathematical modelling was done for the purpose of simulation using MATLAB. Using the working principle of each process and theoretical knowledge, digraph was developed for each process. The variables were denoted by nodes and the relationship among them by continuous and dashed lines. Once the digraph was developed, simulation of each process was carried out and the results compared to the digraph in order to validate it.

The disadvantage of the digraph method is that fault detection is only qualitative which reduces the resolution of fault detection. Also a variable value may fluctuate due to the action of control loops giving compensatory variables (CV) or inverse variables (IV) and the fault diagnostic system should be efficient enough to monitor or predict such changes as well.

Keywords: Fault detection, Digraph method, Process Variables, Compensatory Variables, Inverse Variables

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CHAPTER 1

INTRODUCTION

Background and Objective

1.1.INTRODUCTION

The two primary concerns of any industry are to ensure production of economically efficient and quality goods and to take safety measures for the workers. In chemical industries highly toxic substances are dealt with and an accident can cause huge scale damage such as that in Bhopal Gas Tragedy. It is of utmost importance that faults are detected early and proper steps be taken to repair those faults so that no harm is done either to the workers or to the machinery of the industry. Several sciences like statistics, system science, signal processing, fuzzy logic and computer science have contributed to the development of fault detection and diagnosis (FDD) techniques. FDD generally includes the following steps [1]:

(i) **Fault Detection**: Identification of abnormal system behavior and deviation of process values from their expected ones.

(ii) **Fault Isolation**: Determining the location and accurate cause of the fault among many other possible causes.

(iii) **Fault Identification**: Determination of the magnitude of fault or the degree by which the observed values differ from the expected ones.

Faults can be categorized into three categories: **Sensor Fault, Actuator Fault and Process Fault.** Sensor function is to measure process variable. If the measured value is different from actual variable, it is known as sensor fault. Actuator is the one actually carrying out the operation and provides output. If there is discrepancy between command given to the actuator and the output, it is known as actuator fault.. Process faults include the other faults of the system which may be additive or multiplicative. Additive faults are unknown inputs like a leak whereas multiplicative faults are gradual changes like fouling of heat exchanger surfaces or rusting of iron parts of a machine.

For FDD, two types of methods can be used, model-based method and model-free method. Model-based methods use a mathematically developed model of the process to estimate the correct values of the process variables whereas model-free methods do not use a mathematical model and find faults using defined laws and theories. The performance of FDD is characterized by the following:

(i) **Sensitivity**: It is the ability to detect or diagnose a fault of a specific size. The size of a fault is defined by the range of its effect.

(ii) **Discrimination Power (Isolation Power)**: It is the ability to detect correct fault when several faults happen simultaneously mask each other.

(iii) **Robustness**: It is the ability to detect a fault among noise, disturbance and modeling errors.

(iv) **Missed Fault Detection and False Alarm**: It indicates the number of faults that went undetected and the number of times alarm was issued when there were no faults.

(v) **Detection and Diagnosis Speed**: Indicates time taken by the system to detect and diagnose faults after their occurrence.

Redundancy is an important criterion in FDD. If duplicate sensors are used to detect a fault, it is called physical redundancy. If a process model is used to estimate process variables and the difference between measured and estimated values forms the basis of diagnosis, then it is called analytical redundancy. Physical redundancy is expensive as more hardware is required and concentrates on one variable.

Faults can be further classified into abrupt (sudden faults) and incipient (slowly developing faults). Abrupt faults are dangerous and need to be detected immediately. Incipient faults develop over a period of time, e.g., deposits on heat transfer surface in an exchanger. They are difficult to detect and model-based techniques are more useful in such cases. Time behavior of faults can be classified into:

(i) **Jump**: Jump in sensor reading is generally caused by bias change or breakdown.

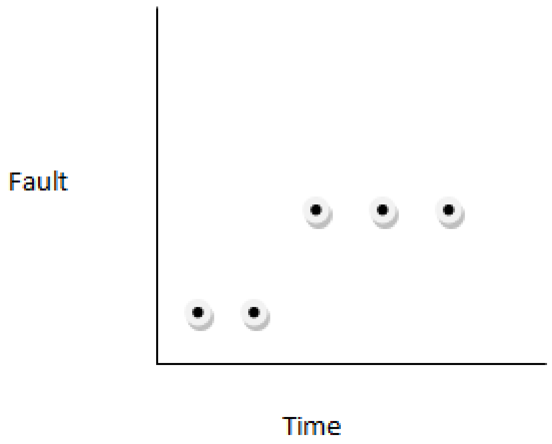

Figure 1.1: Jump fault behaviour

(ii) **Intermittent**: Loose wiring or erroneous data recording results in intermittent fault-time behavior.

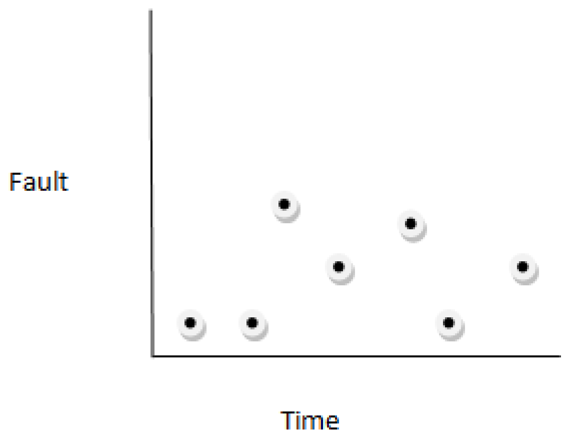

Figure 1.2: Intermittent fault behaviour

(iii) **Drift**: If the sensor is warming up or actuator is wearing out, it results in drift fault time behavior.

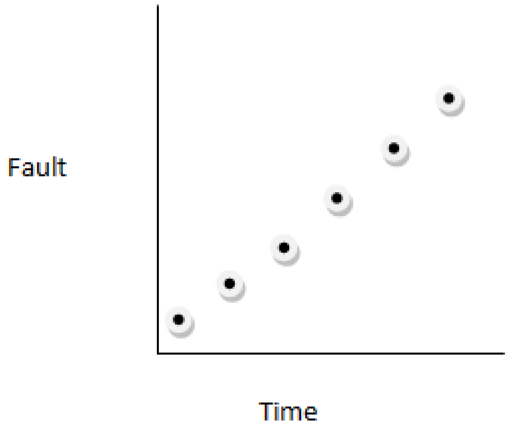

Figure 1.3: Drift Fault Behaviour

In model-based fault detection, a mathematical model of the fault is used and estimation of variables is done based on the model. Then the measured values are compared to estimated values. The difference between these two values is called residual and residuals indicate the presence of faults.

The digraph method is the mode of fault detection that has been studied in this paper. Digraph method, unlike other mathematical models, does not give a quantitative idea of the process under study. Rather mathematical modelling of the process is carried out beforehand and the obtained residues indicate fault, after which the role of digraph comes in.The greatest advantage of the digraph method is the utter simplicity of the figure obtained; even a layman can figure out the relationship between the various process variables and how they affect each other. Digraphs are prone to errors; to validate a given digraph, simulation results of the particular process come to use. Once the tedious task of validating the digraph is over, fault detection by back-tracing through the digraph is child’s play.

CHAPTER 2

LITERATURE REVIEW

The Digraph Method Fundamentals

2.1. THE DIGRAPH METHOD

Digraph, also known as directed graph illustrates the fault propagation through a system. It comprises of a set of nodes (V) representing the system process variables and edges (E) representing the relation between the nodes. The digraph model is represented by:

$$DG = (V,E)$$

Examples of nodes/process variables: Temperature, pressure, mass flow rate, signals from sensors. Digraphs, being qualitative in nature, deviations in variables in digraphs may be represented by five discrete values: +10 (very high), +1 (moderate high), 0 (normal), -1 (moderate low) and -10 (high low).

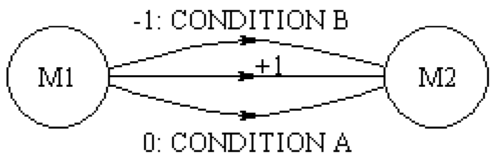

Figure 2.1: A simple digraph representation [2]

In the above figure, M1 and M2 are representing mass flow rates at location 1 and 2. M1 is independent and M2 is dependent. This figure indicates that under normal conditions, the +1 edge represents the relationship between the two nodes. The two other edges are applicable only if the mentioned conditions are satisfied. The gain of such a loop is given by:

$$\text{Gain} = \Delta(M2)/\Delta(M1)$$

Control loops are present in the process and they consist of sensor, controller and control device. Two basic control loops that can be represented by digraphs:

(i) **Negative Feedback Loops**: Corrects moderate deviations in variables. Path on a digraph start and end on the same node and product of all normal gains around this loop is negative. It measures the output, finds the difference between set-point and output and thus controls the output.

(ii) **Negative Feedforward Loops**: In theory, any disturbance can be cancelled in this loop but practically that is not possible. In digraph, represented as two or more paths from one node to another node and sign of product of all normal gains is different on each of the paths. Feedforward controllers measure load directly and accordingly control output.

Negative loops are very important in any process as they play the role of stabilizers. If we have a positive loop and the gain is positive, it means disturbance in a particular direction in a variable will lead to similar disturbances in other related variables and the fault will keep on multiplying until it gets out of control. On the other hand, if there is a negative gain between two variables, then an increase in one will lead to a decrease in the other and this counter effect stabilizes the system. By drawing a digraph of a system, we can accurately keep track of the number of negative and positive loops and try to keep the number of negative loops to maximum.

Following is the example of a water tank system, courtesy literature review, in which the use of digraph method has been studied to determine the causes of possible faults [2].

2.2. <u>THE WATER TANK SYSTEM</u>

It is the simplest system to explain the digraph method. The schematic diagram is given below:

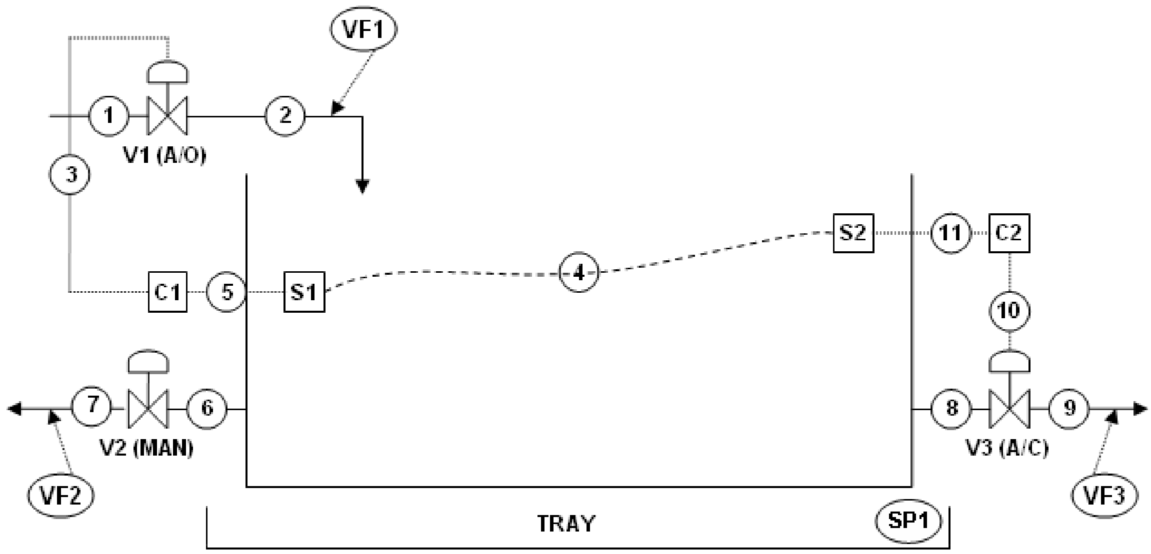

Figure 2.2: Water tank system [2]

The aim of this arrangement is to maintain the level of water between pre-determined levels. The water level is monitored by sensor1 (S1). Under normal conditions, water flows in through the valve1 (V1) and flows out through valve2 (V2). Valve V3 is given as a safety valve. The tray is provided to collect water from any leakage or spill due to overflow.

2.2.1. DETAILS OF THE SYSTEM

The system consists of three valves V1-3, two level sensors S1-2, two controllers C1-2 and a spill tray. S1 senses the level of water and sends signal to controller C1 which in turn controls the valve V1. If the level raises more than the desired level, the controller sends command to V1 to shut down so that supply from mains is cut off and water is drained out. When the water level drops V1 is opened by C1 allowing water in. V2 is a manual valve and thus no controller is associated with it. V3 is a safety valve and is dormant under normal conditions. In case if C1 fails and water level becomes very high, the sensor S2 detects the level and sends signal to C2 which in turn opens V3 to let the excess water out. Even after that if overflow occurs and water is spilled then it is stored in the tray. Control loop 2 is thus redundant until control loop 1 is working properly. The flow sensors VF1-3 measure the flow-rates through the valves V1-3. A sensor SP1 is located in the tank to inform whether there is a leak or not.

2.2.2. OPERATING MODES

There are two operating modes: Active and Dormant. In active state, the valves V1 and V2 are open and V3 is closed. The system is dormant when all the valves are closed.

2.2.3. STEPS FOR DEVELOPING DIGRAPH

There is a step by step process of developing digraph of a system.

(i) The process to be analyzed is defined in details.

(ii) All the possible component failures are considered.

(iii) The system is classified into sub-systems and components.

(iv) The control loops present in the system are identified.

(v) The digraphs of sub-systems are developed first by considering all process variable deviations and the effect they have on the variable present in the model. Also the magnitude of the effect is to be represented by using the values of 10, 1, 0, -1 and -10.

(vi) The models of sub-systems are joined to form the digraph of the whole system.

(vii) Causes of faults are detected by back-tracing from the node showing fault.

2.2.4. WATER TANK DIGRAPH

The following assumptions are made while making the digraph:

(i) If there is a pipe rupture, it is not detected by flow sensors.

(ii) A rupture in the tank causes more volume loss than a tank leakage.

(iii) The system is at steady state initially.

Digraph for each sub-unit is developed as shown in the figures below. The digraphs are constructed based on the proper knowledge of the process and the components, basic laws of science and human reasoning. The variables are represented by:

M= mass flow rate; L= level; P= pressure

Control loops within the water tank system arerepresented as negative feedback loops (NFBL), where the product of the normal gains around the loop isnegative. NFBL's are used since they introduce theability to correct any moderate disturbances which maybe present in one of the process variables.

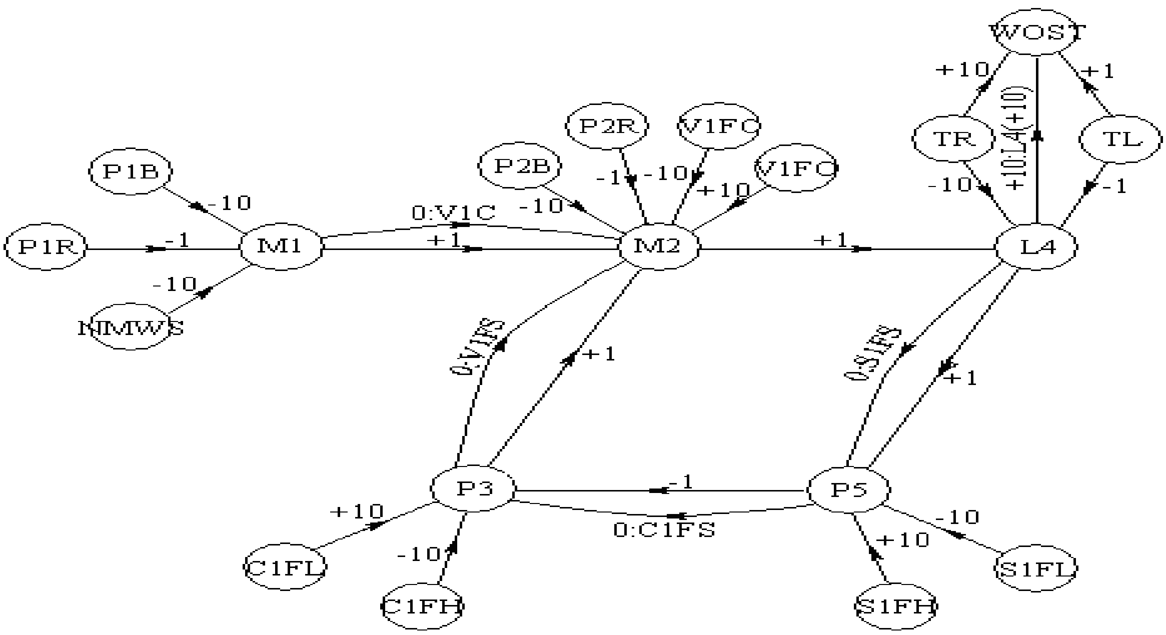

Figure 2.3: SDG of water tank system [2]

The air to open characteristics of V1 is represented by the relationship between M1, M2 and P3. The control action of C1 is represented by the negative feedback loop of M2-L4-P5-P3; it is a negative feedback loop as the product of normal gains is negative. Now the positive "signed" edges represent a directly proportional relation between the two nodes where as the negative "signed" edges show an inversely proportional relation. The magnitude 1, 10 or 0 just represent the degree of effect either positive or negative. Now let us take a look at the various possible faults and their causes. M1 entering V1 can be affected by three kinds of component failures P1B, P1R or NMWS, all of which will decrease the mass flow. Checking the node M2, we see that M2 can be affected by four types of component failure: P2B, P2R and V1FC decrease M2 whereas V1FO increases the mass flow M2. M2 is also related to M1 via two ways. In the normal condition, an increase in M1 increases M2 proportionately. But in case V1 does not work (given by condition V1C), there is no effect of M1 on M2. A disturbance in the control loop M2-L4-P5-P3 can also disturb M2.

Concentrating on the control loop, let us assume that M2 increases. As positive relation exists between M2 and L4, the level of water in tank L4 also increases which is detected by a sensor and it sends a high signal, in this case P5 (higher pressure) to the controller. There is an inverse relation between P5 and P3 which means that the controller on receiving high signal from P5 gives a low signal to P3 (lower pressure). As V1 is an air to open valve, it closes due to low pressure P3 and M2 decreases. This results in the reduction of water level. If M2 decreases for some reason then just the reverse action takes place and liquid level becomes higher. TR (tank rupture) and TL (tank leak) as obvious will have a negative effect on liquid water level and positive effect on water collected in the tray. Similarly based on logical reasoning other nodes can be studied and interlinked to each other. The digraph for the manual valve V2 is given in figure 2.4.

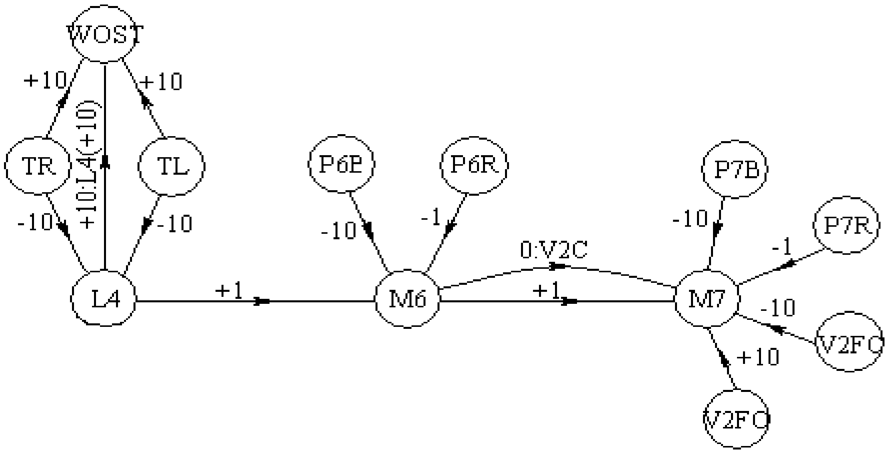

Figure 2.4: Valve 2 (V2) unit digraph [2]

The different component failures affecting M6 and M7 are shown. An increase in L4, increases M6 which in turn increases M7. The relation between M6 and M7 is nullified if V2 is closed.

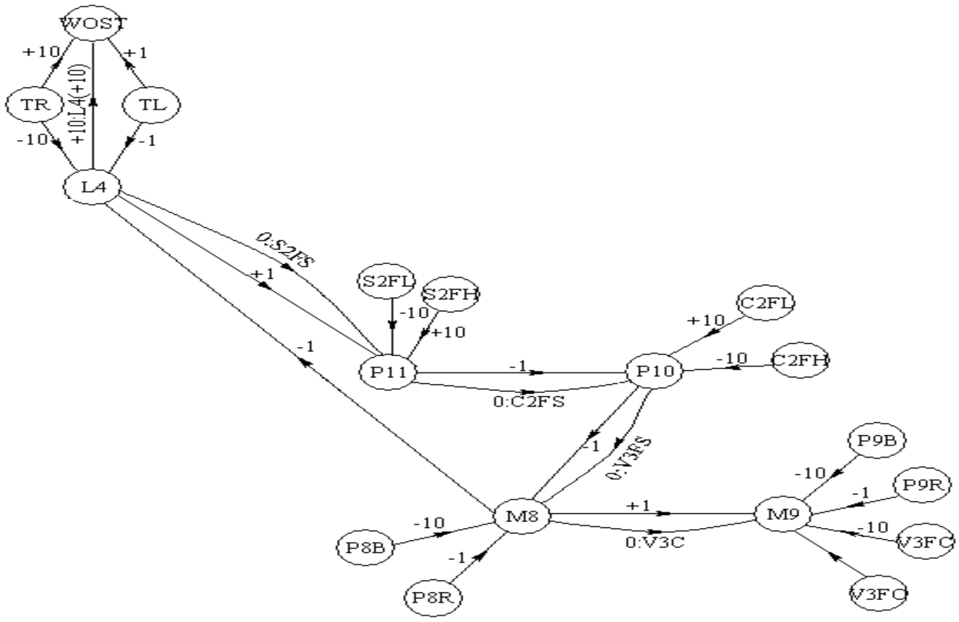

Figure 2.5: Valve 3 (V3) and control loop (C2) unit digraph [2]

Figure 2.5 illustrates the air to close valve V3 through the relationship between M8, M9 and P10. The loop M8-L4-P11-P10 depicts the negative control loops; here also the product of normal gains is negative. If the level becomes very high sensor S2 sends a high pressure signal (P11) to the controller. Negative relation exists between P11 and P10, hence the controller sends a low signal (P10) to the valve. As V3 is air to close valve, low pressure opens the valve and flow increases giving high M8 and M9.

The complete digraph system shown in figure 2.6 is obtained by combining figures 2.3, 2.4 and 2.5.

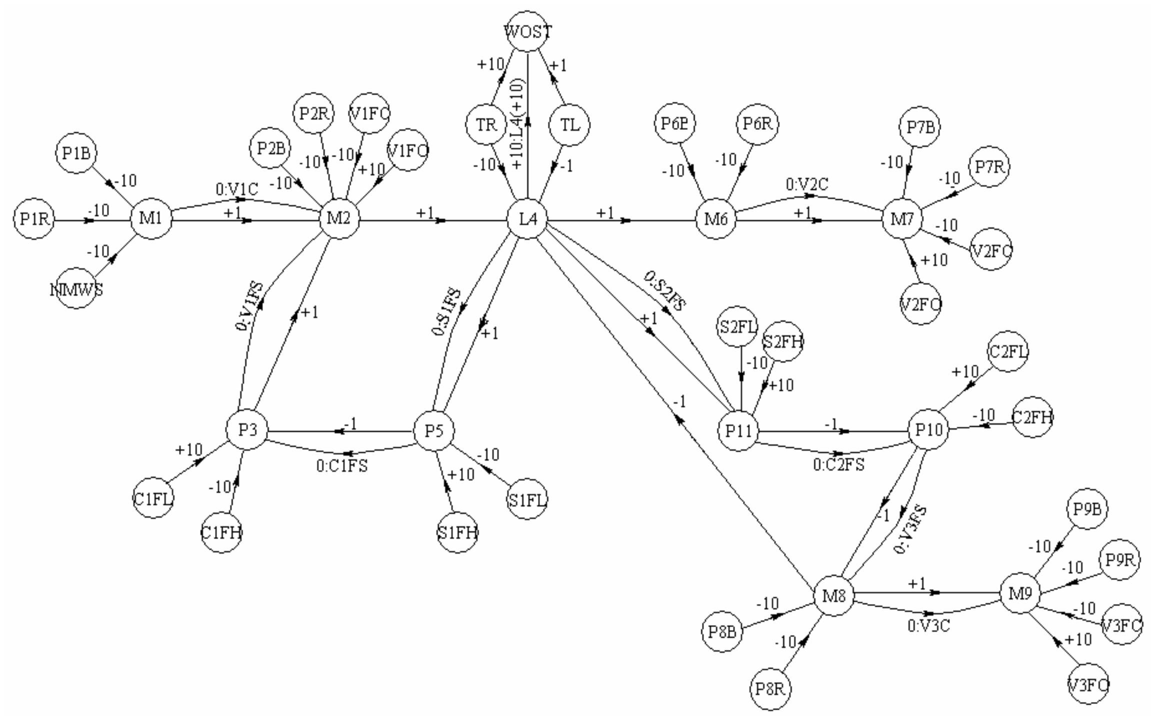

Figure 2.6: SDG of the whole system [2]

2.2.5. DIGRAPH DIAGNOSTIC METHODS

For fault diagnosis, the system sensor readings are compared with the expected values while the system is in operating mode. If a node registers a deviation, diagnosis involves back-tracing from the node through which it is possible to determine the failure nodes. Back-tracing is done until all the nodes possibly causing the fault are marked. It is done in two ways:

(i) **Method One**: In this approach back-tracing is done from the faulty node until the point where no further back-tracing is possible. The disadvantage is that many fault options are generated for a single fault and some of them are contradictory. So this creates an ambiguous situation.

(ii) **Method Two**: From sensor readings it is observed that which particular areas is showing deviation and that particular area is flagged off for back-tracing, leaving the non-deviating nodes intact. Back-tracing from a node ceases as soon as the boundary of flagged section is reached. This method is particularly useful in case multiple sensor faults.

Let us consider an example of Method Two. A deviation from the normal active mode is taken in which VF1 and VF2 are registering no flow. As there is no problem with VF3 or SP1, the part of digraph containing these nodes is flagged off. Now no flow in V1 will cause M2 to decrease which can be caused by P2B, P2R or V1FC. It could also have been caused by decrease in M1 which in turn could have been caused by P1R, P1B or NMWS. Going by the control loop, the decrease in M2 can also be caused due to high liquid level L4. Similar reasoning can be applied to the no flow condition registered by VF2.

Another example taken from literature review, illustrating the use of digraph method, is the PVC plant [3].

2.3. <u>**PVC PLANT**</u>

In a PVC plant, hydrogen and chlorine are obtained by electrolysis and coupling reaction of hydrogen and chlorine is done to produce hydrochloric gas. Part of the process is represented by the digraph given below [4]:

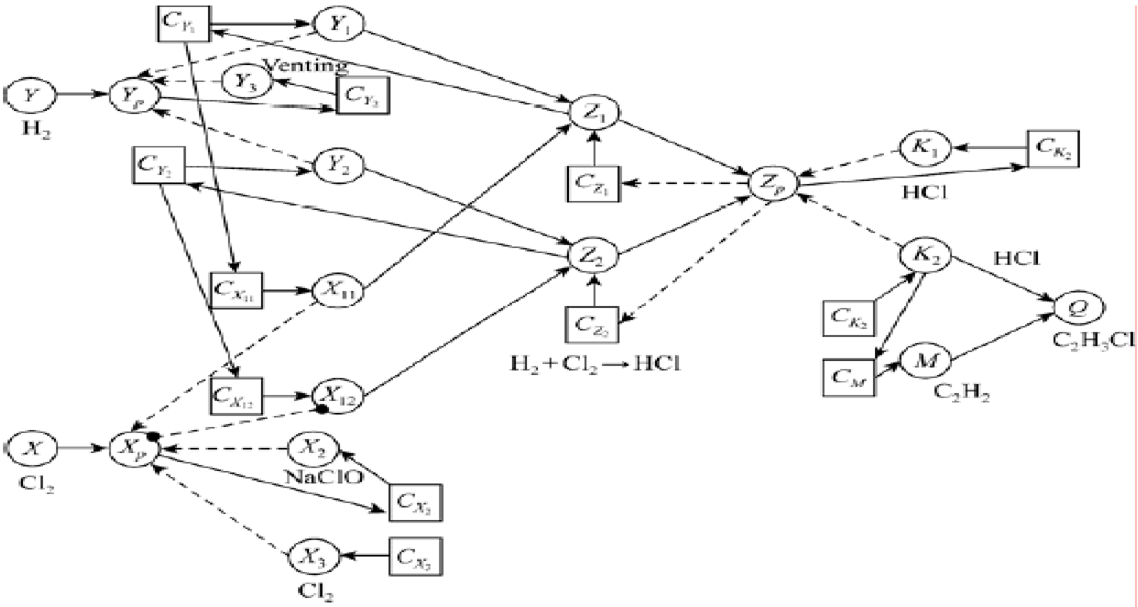

Figure 2.7: SDG of a PVC plant (partially) [4]

This figure can be used to determine the types and number of control loops present in the system. The order of a loop is nothing but the number of nodes present in the loop. As already mentioned above, the loop the product of normal gains of whose edges is negative is a negative loop otherwise it is positive. A positive loop is dangerous from safety point of view as the effect of deviation whether increasing or decreasing, advances or goes on multiplying making the system unstable. To make a system stable more and more negative loops are used so that no one effect dominates and contradictory effects exist to balance.

In the above figure we see there are two 3-order positive loops: Cy1-Y1-Z1 and Cy2-Y2-Z2. There are four 3-order negative loops: Cz1-Z1-Zp; Ck2-K1-Zp; Cz2-Z2-Zp and Cx2-X2-Xp. Similarly there are positive and negative 4-order loops. The complete list of number and types of loops related to a node is known as its loop status. The loop status of nodes in the above digraph is given in the following table.

Table 2.1: Loop status of nodes in PVC plant (partial)[4]

Node	3 order positive loop	4 order positive loop	3 order negative loop	4 order negative loop
X_p	0	0	1	0
X_{11}	0	0	0	1
$C_{X_{11}}$	0	0	0	1
X_{12}	0	0	0	1
$C_{X_{12}}$	0	0	0	1
X_2	0	0	1	0
C_{X_2}	0	0	1	0
Y_p	0	0	1	0
Y_1	0	0	1	0
C_{Y_1}	0	0	1	1
Y_2	0	0	1	0
C_{Y_2}	0	0	1	1
Y_3	0	0	1	0
C_{Y_3}	0	0	1	0
Z_1	0	0	2	1
C_{Z_1}	0	0	1	0
Z_2	0	0	2	1
C_{Z_2}	0	0	1	0
Z_p	0	0	3	0
K_1	0	0	1	0
C_{K_1}	0	0	1	0

Following chapters are based on the three processes that have been studied as a part of this project and their digraphs have been developed.

CHAPTER 3

JACKETED NON-ISOTHERMAL CONTINUOUS STIRRED TANK REACTOR

Mathematical modeling

Development of digraph

3.1 INTRODUCTION

A JCSTR was used for analyzing the effect of deviation in one variable on all the other variables. Liqiang Wang [5] has shown that in this case, fault in one node propagates through various pathways and the most dominant of these pathways is determined. The concept of compensatory response (CR) and inverse response (IR) has also been explained by Wang. To study the concept of CR and IR, three qualitative states are identified: 0 (normal), +1 (high) and -1 (low). It is assumed that initially all the nodes are at steady state and hence are assigned 0 before fault is introduced. When a fault occurs, deviation of the root node causes all variables accessible from the root node to change sign. The first sign change (0 to +1 or 0 to -1) is considered as the initial response of the system. Due to the presence of numerous feed forward and negative feedback loops and control action, the signs of variables may change during propagation of the fault. The final state or ultimate response of a node can be to retain the initial state; return to the steady state or to have the inverse state. If the variable returns to the steady state value of 0, then it is known as compensatory variable (CV) and if the variable takes the opposite value of that in initial response, then it is known as inverse variable (IV). The whole rule base for fault detection has three parts: the normal state before fault introduction, the initial and ultimate response after fault introduction.

The JCSTR model is given in figure 3.1. The objective was to control the volume in the tank at desired value using the level control (LC) loop. As a non-isothermal reactor was considered, temperature could vary but extreme values had to be avoided. Hence, cold water was circulated through the jacket to cool the reaction solution inside the reactor heated up by an exothermic reaction. The volume was controlled by adjusting the tank outflow and the temperature was controlled by adjusting cold water inflow valve. Assumptions made were that no phase change occurs either in the tank or the jacket. Also the jacket volume, density and heat capacity of fluids remain constant. Heat transfer to surroundings was neglected.

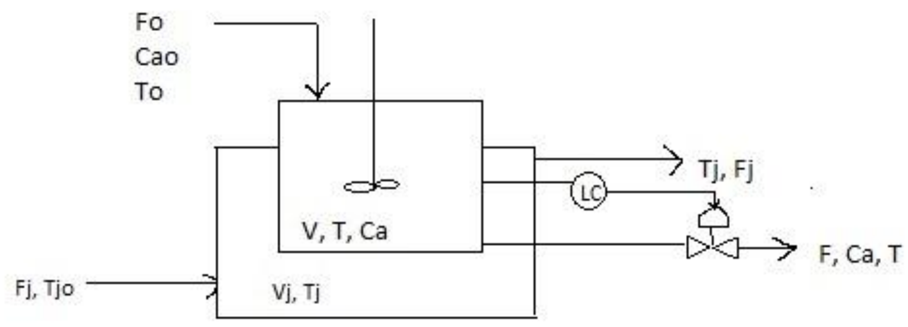

Figure 3.1: Jacketed non-isothermal CSTR model along with level controller

Mass balance inside the reactor:

$$\frac{dV}{dt} = F_o - F \qquad \text{(Assuming constant density)} \qquad (3.1)$$

Component Balance inside the reactor:

$$\frac{d(VCa)}{dt} = F_o C_{ao} - FC_a - V(kC_a{}^n) \qquad (3.2)$$

Energy Balance in the reactor:

$$\frac{d(\rho Vh)}{dt} = \rho F_o h_o - \rho Fh + \lambda V\rho(kC_a{}^n) - UA\big(T - T_j\big) \qquad (3.3)$$

Energy Balance inside the jacket:

$$\frac{\rho_j d\big(V_j h_j\big)}{dt} = \rho_j F_j h_{jo} - \rho_j F_j h_j + UA(T - T_j) \qquad (3.4)$$

These are the four equations of state which tell us about the behavior of the system and these equations are used for the simulation of the jacketed CSTR. Now, in any system, there are some variables and some equations. Under ideal conditions, the number of equations is equal to the number of variables and all the variables have unique values. When the number of equations is more than the number of variables, there is no feasible solution of the system. Again, if the number of variables is greater than the number of equations, then there are infinitely many solutions as the variables can take any arbitrary value. Keeping the above points in mind, it is very important to check the degree of freedom (Number of variables-Number of equations) of any system. In case of a positive degree of freedom, control parameters are introduced to balance the extra variables.

From the above figure, the variables in the JCSTR are: $F_o, C_{a0}, T_o, F_j, T_{jo}, T_j, V_j, V, T, C_a \; and \; F$

Total we get 11 variables. But out of these 11, $F_j \; and \; V_j$ are constant as the jacket volume remains constant. Thus the actual number of variables is 9. Hence degree of freedom:

Degree of Freedom= 9-4 =5

Out of these 5 degrees of freedom, F_o, C_{ao} and T_o can be considered as forcing variables or disturbances that can be controlled manually. The rest 2 can be balanced by the following equations:

Level Controller Equation:

$$F = K_v(V - V_{min}) \tag{3.5}$$

Here we can see that F is the manipulated variable and V is the controlled variable (indirectly, as we are controlling the height). Kv represents the outflow valve attached to the level controller.

Heat Transfer Equation:

$$Q = UA\,(T - T_j) \tag{3.6}$$

Where

$$A = \frac{\pi {D_r}^2}{4} + \frac{4V}{D_r} \tag{3.7}$$

After the development of mathematical model of the process, its digraph was developed. The digraph is shown in figure 3.2.

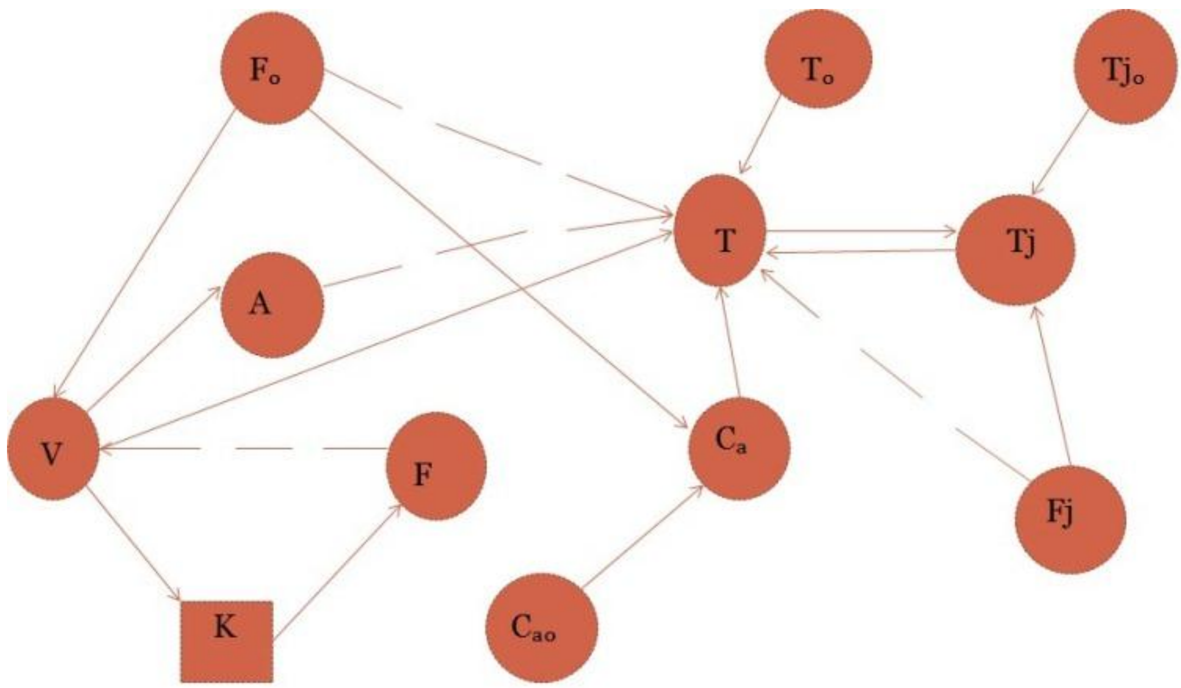

Figure 3.2: SDG Model of JCSTR

3.2FAULT ANALYSIS

In the above digraph, the continuous lines between two variables suggest a directly proportional relationship between the two, whereas the dashed lines represent inversely proportional relationship. The direction of effect is represented by the direction of the arrow. This digraph consists of one three-order negative loop and no positive loops and thus is stable. A probable disturbance was assumed and its propagation through the system was observed. The propagation of fault through the system, when back-traced from the node showing fault, gives us the originating node.

A sudden increase in the inflow rate F_o was assumed. The consequent effects on other variables as traced in the digraph are:

(i) Fo ----→ V ; thus V increases

(ii) Fo --→V ---→ F ; thus outflow rate F increases to bring down V

(iii) Fo --→ V --→ A --→ T; hence T decreases. This is because when V increases, the area of heat transfer increases and more heat is given out to the jacket. Hence, temperature inside the tank is reduced.

(iv) Fo -→Ca; the concentration of reactant increases with increase in inflow rate

(v) Fo --→Ca ---→ T; as reactant concentration increases, reaction rate is faster and more heat is released

(vi) Fo -→ T --→Tj; Tj decreases. Due to low inside temperature, jacket fluid does not heat up much

(vii) Fo -→ V --→ A --→ T --→Tj; Tj decreases

(viii) Fo ----→Ca ---→ T ---→Tj; Tj increases

In the last three points it was observed that contradictory results were obtained. In two cases, Tj decreased with an increase in inflow rate. But in the last case Tj increased with increase in flow rate. In any process, a particular variable is affected by many other variables and their effects may be contradictory. According to work carried out by AtallaSayda[6], such problems can be overcome with the help of simulation. If the Tj versus time graph shows a positive slope when Fo is changed positively, path (viii) is dominant. On the other hand, if Tj versus time shows negative slope with an increase in Fo, any of the pathways (vi) or (vii) is dominant. To decide which among the two is more dominant, the slopes of the corresponding graphs are compared. The one with a steeper slope will have higher dominance.

3.3 COMPENSATORY VARIABLE AND INVERSE VARIABLE

Now, let us test the theory of CV and IV. For this purpose, pathway (viii) was assumed to be dominant, i.e., Tj increases when Fo increases. Any other pathway can also be assumed. The measured out variables of the system are F, T, Ca, V, Tj. These five variables are represented in a set: S [F, T, Ca, V, Tj]. (+) sign indicates a positive deviation and (-) indicates negative deviation. In case of Fo(+), the initial response of the system (IR) is as follows: S [+, -, +, +, +]. But after some time, the controller C1 will come into action whose objective is to maintain desirable V value. As V goes on increasing, the controller will try to counter the effect with the help of manipulating variable F. Thus the final steady state condition is that V is decreased. The final result after controller action is known as the ultimate response (UR). The controller may bring the value of V to the initial steady state value (represented by 0). Thus the ultimate response will be S [+, -, +, 0, +]. In his case the variable V is known as compensatory variable or CV. But if the controller action overshoots the steady value and the final value of V shows a negative deviation, then the ultimate response is S [+, -, +, -, +]. In this case the variable V is known as inverse variable or IV.

CHAPTER 4

BINARY DISTILLATION COLUMN

Mathematical modelling

Development of digraph

4.1 INTRODUCTION

The working of distillation column was studied in detail, its mathematical modeling done and then its digraph prepared. The digraph was validated after simulating the model in MATLAB. The schematic diagram of the distillation column is given below:

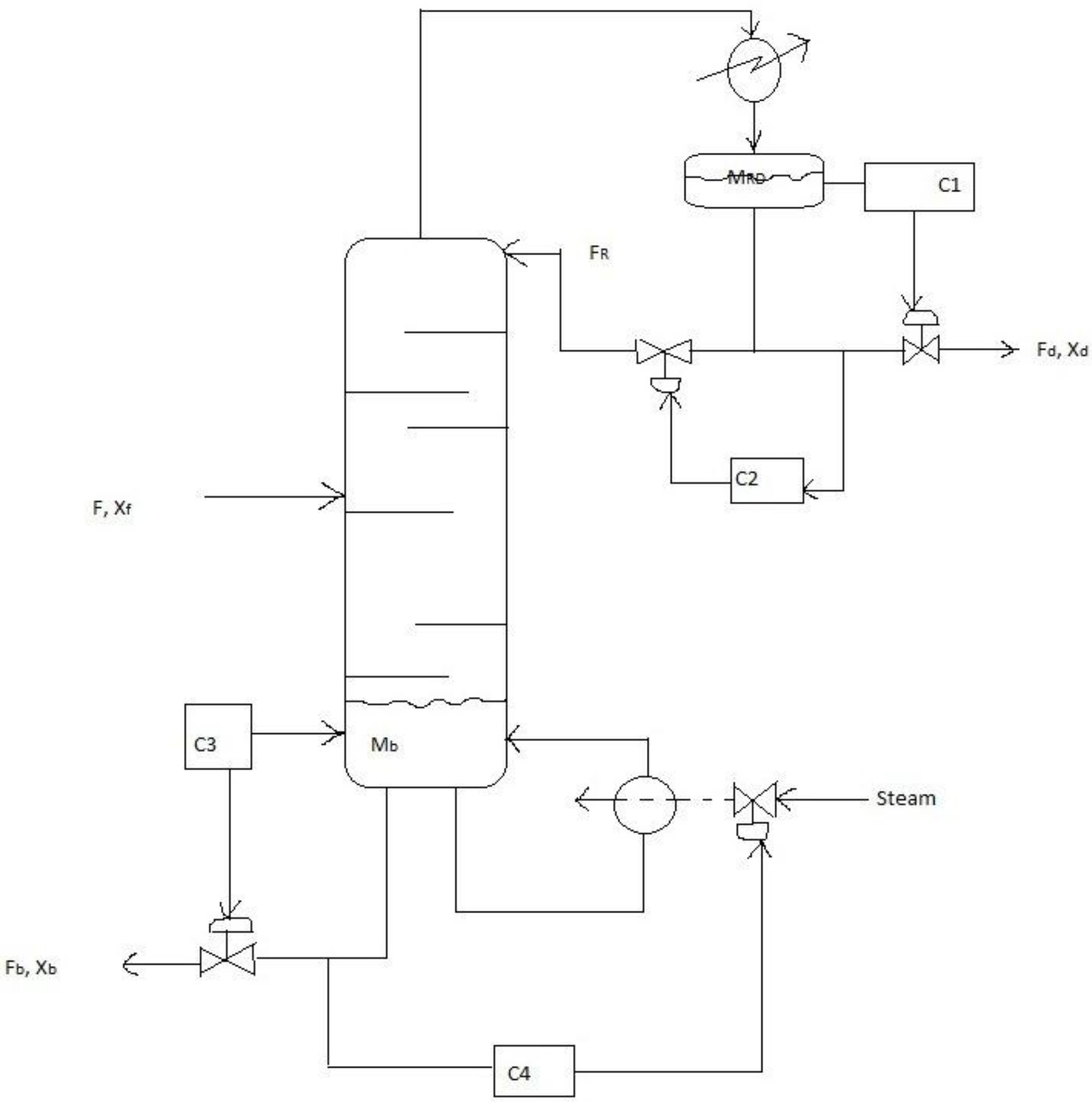

Figure 4.1: Schematic diagram of a distillation column

The following assumptions were made while studying the system [7]:

(i) There are N trays in the column and all the trays are 100 % efficient

(ii) The molal vapor flow-rate remains constant throughout the tower

(iii) The heat of vaporization of the down-coming fluid is almost equal to the heat of condensation of the upcoming vapour; sensible heat difference are also same

(iv) There is no heat loss to the surrounding

(v) The liquid flow rate from each tray depends on its liquid hold-up

(vi) Vapour hold-up on each tray is neglected

(vii) Relative velocity of the two components remains constant throughout the tower and momentum balance on each tray is neglected

Mass balance in feed plate (i=f):

$$\frac{d(M_f)}{dt} = L_{f+1} - L_f + F_f \tag{4.1}$$

Component balance in feed plate (i=f):

$$\frac{d(M_f x_f)}{dt} = L_{f+1}x_{f+1} - L_f x_f + V_{f-1}y_{f-1} - V_f y_f \tag{4.2}$$

Mass balance for top plate (i=N):

$$\frac{dM_n}{dt} = F_R - L_N \tag{4.3}$$

Component balance for top plate (i=N):

$$\frac{d(M_N x_N)}{dt} = F_R x_D - L_N x_N + V_{N-1}y_{N-1} - V_N y_N \tag{4.4}$$

Mass balance for bottom tray:

$$\frac{dM_1}{dt} = L_2 - L_1 \tag{4.5}$$

Component balance for bottom tray:

$$\frac{d(M_1 x_1)}{dt} = L_2 x_2 - L_1 x_1 + V y_B - V_1 y_1 \tag{4.6}$$

Mass balance for rest trays:

$$\frac{dM_i}{dt} = L_{i+1} - L_i \tag{4.7}$$

Component balance for rest trays:

$$\frac{d(M_i x_i)}{dt} = L_{i+1} x_{i+1} - L_i x_i + V_{i-1} y_{i-1} - V_i y_i \tag{4.8}$$

Mass balance for reflux drum:

$$\frac{dM_{RD}}{dt} = V_N - F_R - F_D \tag{4.9}$$

Component balance for reflux drum:

$$\frac{d(M_{RD} x_D)}{dt} = V_N y_N - (F_R + F_D) x_D \tag{4.10}$$

Mass balance for column base:

$$\frac{dM_B}{dt} = L_1 - V - F_B \tag{4.11}$$

Component balance for column base:

$$\frac{d(M_B x_B)}{dt} = L_1 x_1 - V y_B - F_B x_B \tag{4.12}$$

The above were differential equations. The algebraic equations governing the process are:

Equilibrium relation:

$$y_i = \alpha x_i / [1 + (\alpha - 1) x_i] \tag{4.13}$$

Francis Weir relation:

$$L_i = f(M_i) \tag{4.14}$$

Total number of variables = 4N+11

Tray liquid and vapour composition (x_i and y_i) = 2N

Tray liquid hold-ups (M_i) = N

Tray liquid flow-rates (L_i) = N

Bottom liquid and vapour composition (x_b and y_b) = 2

Molal vapour flow-rate throughout the tower = 1

Reflux drum composition (x_d) = 1

Reflux flow-rate (F_r) = 1

Distillate flow rate (F_d) = 1

Bottom liquid flow rate (F_b) = 1

Reflux drum and bottom hold-up (M_{rd} and M_b) = 2

Feed flow-rate and composition (F and x_f) = 2

Total number of equations = 4N+5

Tray mass balance = N

Tray component balance = N

Mass balance in reflux drum and bottom = 2

Component balance in reflux drum and bottom = 2

Equilibrium relation on trays = N+1

Francis Weir relation on all trays = N

Hence, degrees of freedom = (4N+11) – (4N+5) = 6

Out of these six, x_f and F can be considered as the forcing variables or disturbances. The rest four degrees of freedom are balanced by the use of four controllers whose control objectives are:

(i) To maintain desirable reflux drum hold-up

(ii) To maintain optimum composition in reflux stream

(iii) To maintain desirable bottom hold-up

(iv) To maintain optimum composition in bottom stream

These four controllers have been shown in figure 4.1 above. Figure 4.2 shows the binary distillation column digraph.

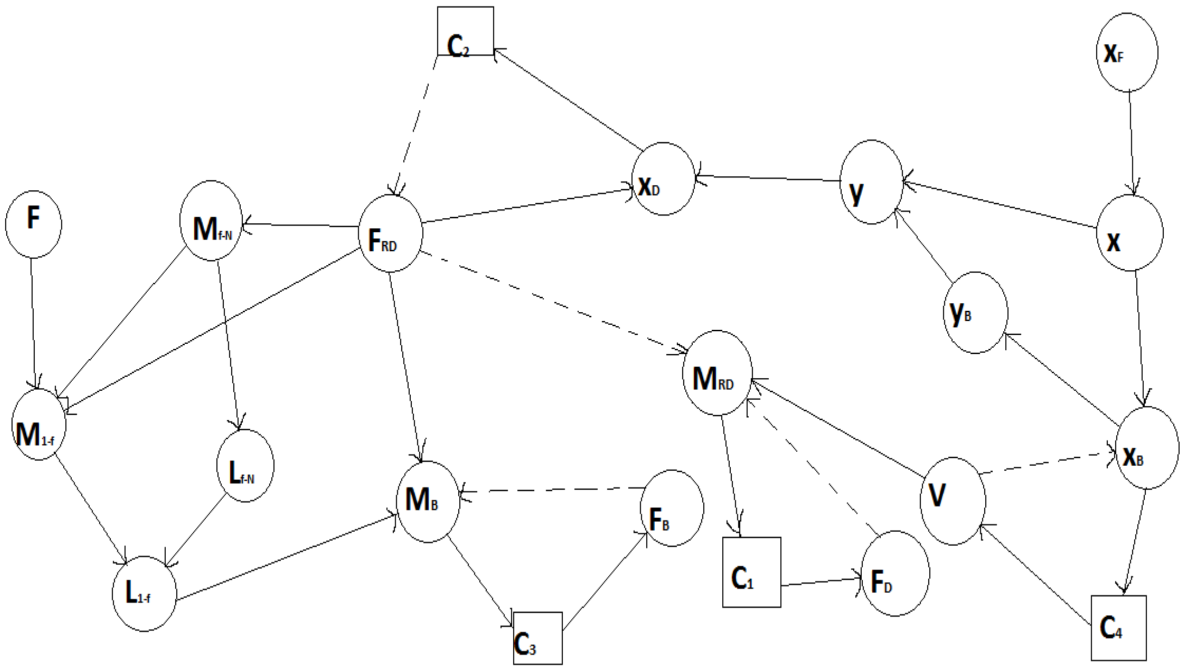

Figure 4.2: SDG of binary distillation column

4.2. DIGRAPH ANALYSIS

In the above digraph, there are four 3-order negative loops and no positive loops. Hence, the system is stable. There are two forcing functions: F and x_f. A probable disturbance was assumed in both the variables and the propagation of fault through the system was observed. If there is a sudden decrease in the feed rate F, the hold up in plates from i=F to i=1 decreases. As the liquid flow rate from trays is a function of the hold-up, the liquid flow-rates (L) of the above mentioned trays are also reduced. Due to low liquid flow rate, the bottom liquid level starts decreasing. The objective of controller C3 is to maintain an optimum level of liquid level in column bottom. When the liquid level reduces below the optimum level, it sends a signal to the controller, which in turn reduces the output flow rate (F_b) of bottom liquid thus stabilizing the liquid level. The propagation of fault induced by disturbances in the other forcing function x_f can be similarly traced out in the digraph.

Now let us test the back-tracing technique by assuming a fault in any random variable. Let it be Mrd. Back-tracing is always done in the direction opposite to that of the arrows as we are tracing the cause and not the effect. If the level sensor is showing negative reading (level lower than desired), then as per the digraph, we can trace the fault through the following paths:

(iv) A positive deviation (increase) in F_{rd}. It is in turn caused by a negative deviation in x_d. The negative deviation can be finally traced back to x_f through the joining lines and thus it may be a possible cause of the original deviation.

(v) Another path is that through V (V decreases). Tracing the lines we see that the negative deviation is finally traced to x_f through x_b and x.

Although we took two different routes to back-trace, we finally reached the same fault root, i.e., a negative deviation in x_f.

CHAPTER 5

DRUM BOILER

Mathematical modelling

Development of digraph

5.1. INTRODUCTION

Drum boiler is a device in which water is the input feed and steam is the output product. It consists of a drum to which water is fed, the water flows down the downcomer connected to the drum; the riser section of the tube is exposed to radiation and thus the water heats up. The steam formed travels back to the drum via connecting tubes. When steam enters the drum, the drum pressure increases. To reduce the pressure inside and bring it to the saturation pressure of the drum liquid, some of the steam is converted back to water while the other fraction escapes the drum through outlet. The schematic diagram of a drum boiler is given in figure 5.1.

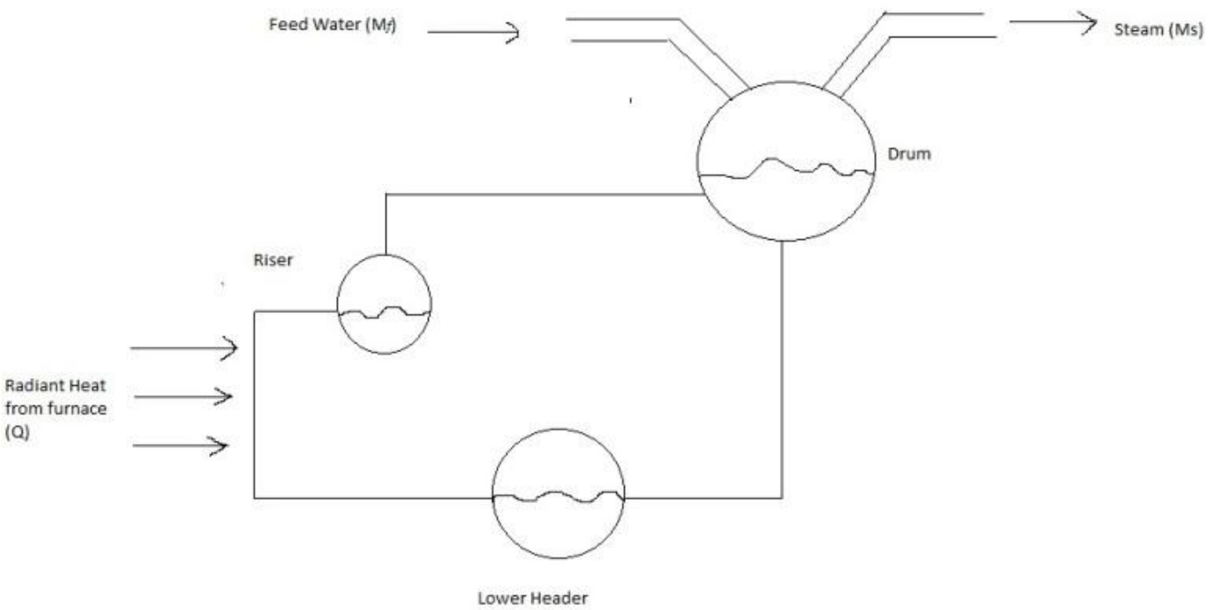

Figure 5.1: Schematic diagram of a drum boiler

The inputs to the system are heat flow to the riser (Q) and the input feed water rate (M_f) while the outputs of the system are the drum level (l) and drum pressure (P). The following assumptions were considered to develop the mathematical model [8]:

(i) Water is in thermodynamic saturated state

(ii) Instantaneous and uniform thermal equilibrium is maintained between water and metal everywhere

(iii) Steam and water readily release and absorb energy with changing pressure

(iv) At steady state metal temperature is very close to the saturation temperature of water and thus there is significant sensible heat transfer

Overall mass balance for the drum boiler:

$$\frac{d[\rho_s V_{st} + \rho_w V_{wt}]}{dt} = M_f - M_s \tag{5.1}$$

Overall energy balance:

$$\frac{d[\rho_s V_{st} h_s + \rho_w V_{wt} h_w - PV_{sd} + m_t C_p t_m]}{dt} = Q + M_f h_f - M_s h_s \tag{5.2}$$

As the water passes through the riser region, it gets heated up by the heat radiation and a mixture of steam and water is formed. To composition of the mixture is denoted in terms of α_ϑ and α_r which represent the volume fraction of vapour and mass fraction of vapour respectively.

Mass balance for riser:

$$\frac{d[\rho_s V_r \alpha_\vartheta + \rho_w V_r (1-\alpha_\vartheta)]}{dt} = q_{dc} - q_r \tag{5.3}$$

Energy balance for riser:

$$\frac{d[\rho_s V_r \alpha_\vartheta h_s + \rho_w V_r (1-\alpha_\vartheta) h_w - PV_r + m_t C_p t_s]}{dt} = Q + q_{dc} h_w - q_r (\alpha_r h_s + h_w) \tag{5.4}$$

The main forces acting on the system are:

(i) Inertial force: $d[q_{dc}(L_r + L_{dc})]/dt$

$= (L_r + L_{dc})\, dq_{dc}/dt$

(ii) Driving force due to vapour-liquid density difference: $(\rho_w - \rho_s)\alpha_\vartheta V_r g$

(iii) Friction force : $K{q_{dc}}^2/2\rho_w A_{dc}$

Thus overall momentum balance for drum boiler:

$$\frac{(L_r+L_{dc})dq_{dc}}{dt} = (\rho_w - \rho_s)\alpha_\vartheta V_r g - K{q_{dc}}^2/2\rho_w A_{dc} \quad (5.5)$$

Drum level (l) is given by:

$$l = (V_{sd} + V_{wd})/A_d \quad (5.6)$$

The above six equations determine the behaviour of the system and are called state equations.

The process variables are: M_f, V_{wd}, V_{sd}, V_{wt}, V_{st}, q_{dc} (= q_r), l, M_s, P, Q, α_r and α_v

Thus total number of variables= 12

Total equations=6

Degrees of freedom= 12-6 = 6

Out of the 12 variables, M_f and Q are forced variables; so we have 4 degrees of freedom to balance. One equation exists between α_v and α_r:

$$\alpha_\vartheta = \rho_w\alpha_r/[\rho_s + (\rho_w - \rho_s)\alpha_r \quad (5.7)$$

The rest three degrees of freedom are balanced by the use of three controllers as is shown in the digraph in figure 5.2.

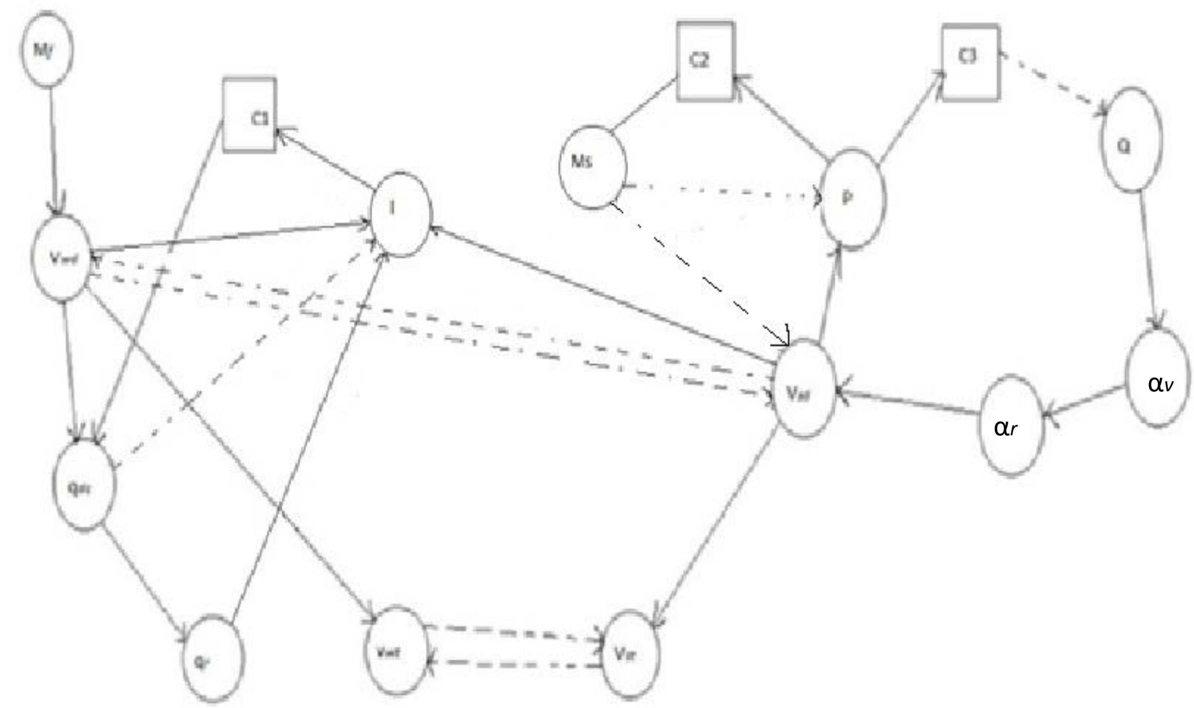

Figure 5.2: SDG of drum boiler

5.2. DIGRAPH ANALYSIS

In the above digraph we can see that there are three 3-order negative loops and no positive loops; hence the system is stable. The objective of the first controller (C1) is to maintain a desired drum level. If the drum level increases, the controller in turn increases flow-rate through the downcomer inevitably reducing the drum level. The objective of the other two controllers C2 and C3 is to maintain safe pressure inside the drum. The manipulated variable in case of C2 and C3 are steam flow rate (M_s) and heat radiation (Q) respectively. The total volume of the system can be calculated by adding total volume of steam (V_{st}) and total volume of water (V_{wt}). As the total volume of system remains constant, V_{st} and V_{wt} have inverse relationship among them, i.e., if one increases then the other decreases.

A sudden positive deviation in feed water flow-rate (M_f) was assumed to test the propagation of fault through the system. The digraph showed an increase in drum level (l) in the above case. This increase is stabilized by controller C1. Increase in Mf also leads to increase in V_{wt} which in turn causes a decrease in V_{st}. Now, if we consider a situation in which the output steam flow rate Ms shows a sudden increase, then following back-tracing technique, we can trace it to an increase in heat radiation (Q) through V_{sd}, α_r and α_v. Thus it is obvious how easy determining the root cause of a fault becomes with the usage of digraph method.

The proposed effects of changes in M_f, M_s and Q on drum level (l) and drum pressure (P) were verified by simulation. The graphs are provided below:

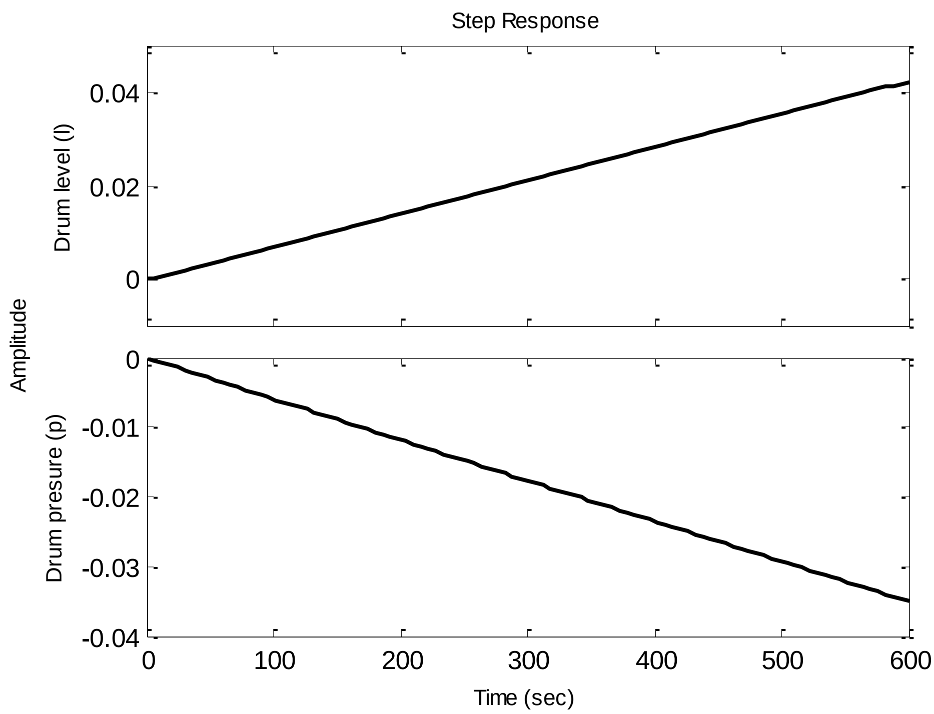

Figure 5.3: Open-loop Response for step increase in Mf

In the digraph, there are three pathways from M_f to l:

(i) M_f--→ V_{wd}--→l

(ii) M_f--→ V_{wd}--→q_{dc}--→l

(iii) $M_f \dashrightarrow V_{wd} \dashrightarrow q_{dc} \dashrightarrow q_r \dashrightarrow l$

Steps (i) and (iii) show an increase in l but (ii) shows a decrease. Thus we again encountered contradictory pathways. From the graph though we can see that path (i) and (iii) dominate as l increases with increase in M_f. Drum pressure P invariable decreases with an increase in M_f.

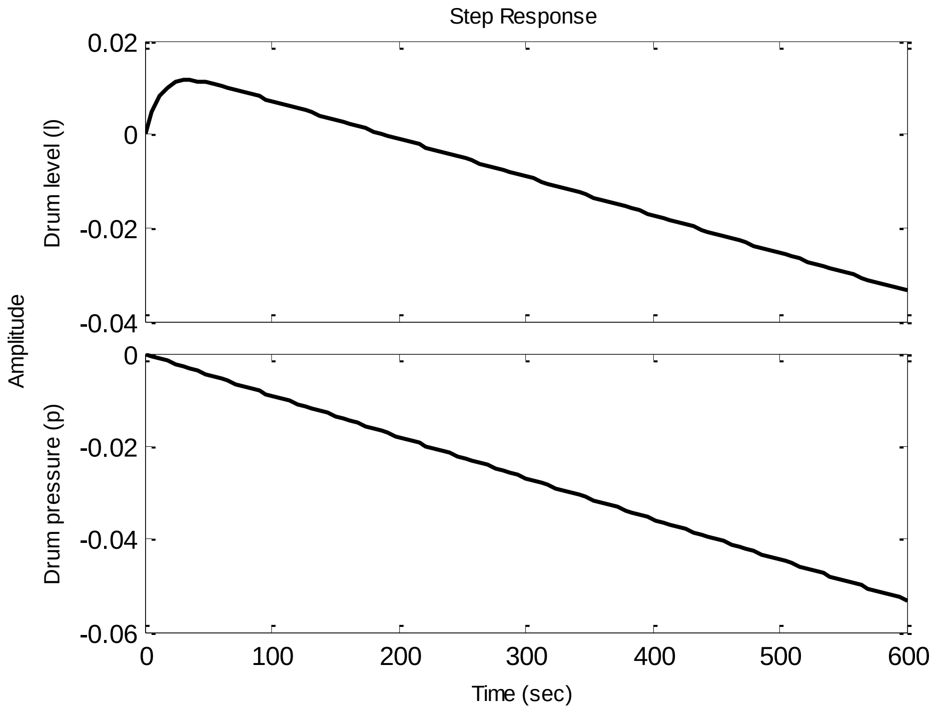

Figure 5.4: Open-loop Response for step increase in Ms

The behaviour of l and P due to step increase in M_s is shown both by digraph and simulation graphs and both the results corroborate each other. Both P and l decrease due to an increase in M_s.

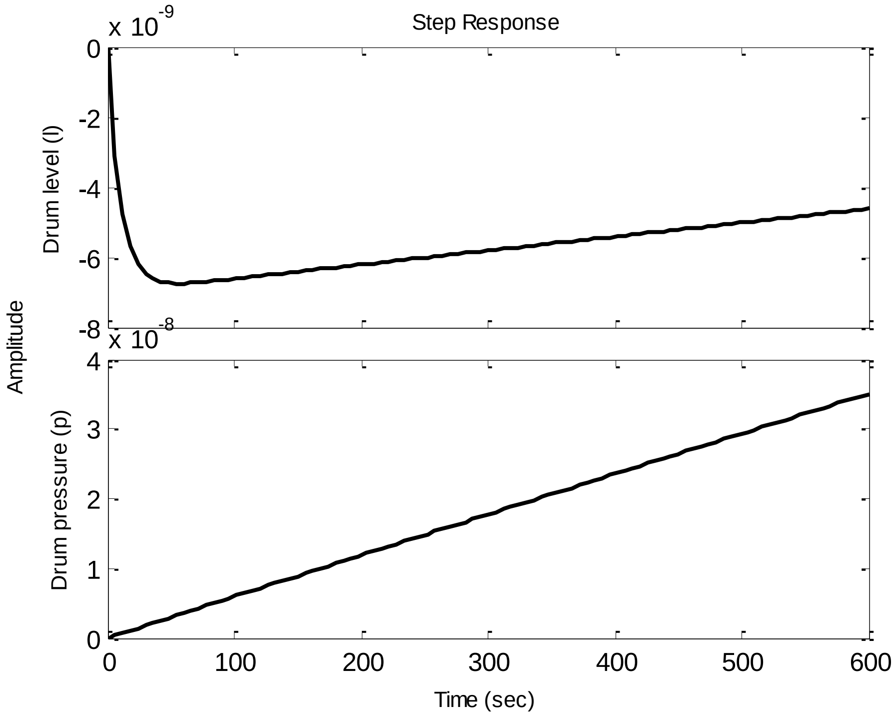

Figure 5.5: Open-loop response for step increase in Q

The increase in heat radiation Q brings about an increase in both l and P. This result is shown in both digraph and figure 5.5. But an extra knowledge that can be derived from the graph is that upon increasing Q, l first decreases then increases. This may happen because as Q is increases, Vsd increases. As more steam enters the drum, more is taken out to reduce pressure and thus initially the drum level drops. This behaviour cannot be shown by the digraph. All these graphs were plotted for open loop system, i.e., without the use of controllers. Figure 5.6. shows the behaviour of l and P under linear quadratic tracking (LQT) controller action.

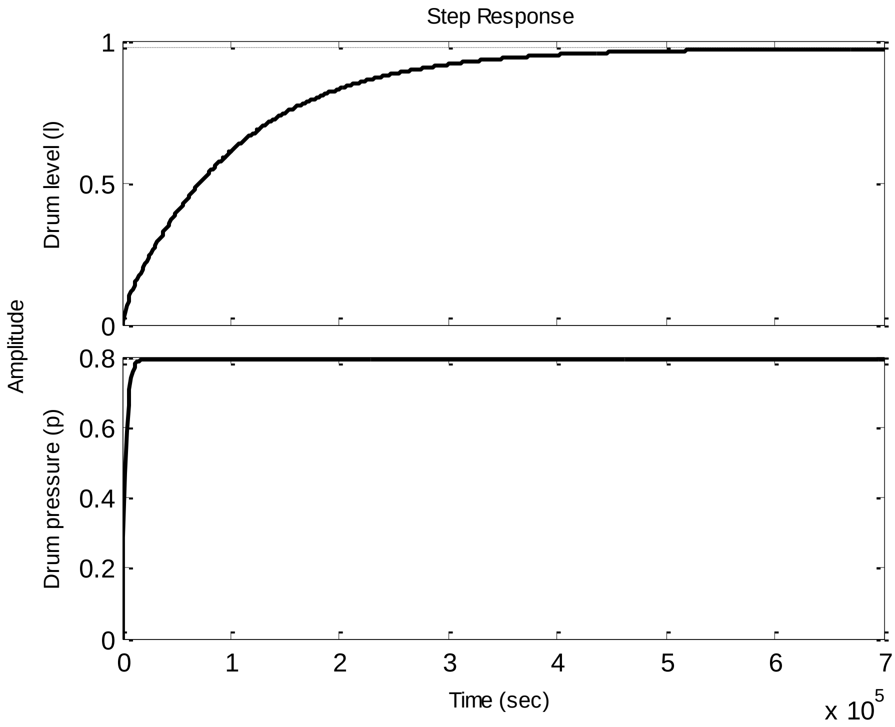

Figure 5.6: Closed-loop response for a step increase in Q

CHAPTER 6

CONCLUSION AND RECOMMENDATION

Possible future work

6.1 CONCLUSION AND RECOMMENDATION

Advantage of digraph method:

(i) The digraph method discusses in detail the various possible faults in a system and the different paths via which it can be propagated, thus giving an exhaustive analysis of the system.

(ii) Simulation results help determine the dominant pathway in case of conflicting effects of other variables on the monitored variable.

(iii) Any arbitrary fault can be traced back to its root cause within no matter of time.

(iv) Digraph, once fully developed and validated, is so easy to study that even an ordinary worker without any special education or technological degree can carry out the task of fault detection and analysis.

Disadvantages of digraph method:

(i) It is a qualitative analysis. The deviations in variables are assigned qualitative states of high (+) and low (-). The actual quantity of increase and decrease cannot be determined.

(ii) The digraph is developed by knowledge of fundamentals and human reasoning; it is susceptible to errors and need many rounds of checking before actual implementation.

These are the major two drawbacks due to which digraph method is still in laboratory scale and has not been practically implemented in any industry.

Since 1990s, researchers have been discussing and experimenting the use of fuzzy logic and fuzzy set theory to improve the diagnostic resolution in SDG-model based approaches. Inclusion of quantitative information may also help in better understanding of the dynamic working of the system and false indication of faults may be reduced. The use of fuzzy logic to help address the problem of setting the threshold (limiting value) of alarm was discussed by Han et al. [9]. In their approach, after the most probable root causes which are the possible fault origins are located, fuzzy logic is introduced. Based on their membership degree of the origin nodes, variables are arranged in an increasing manner and the fault origins having highest memberships are located. This approach was shown to improve the accuracy of diagnosis resolution. Shih and Lee [10, 11] discussed the removal of bogus solutions using fuzzy logic principles with SDGs, and the Fuzzy Cause-Effect Digraph was proposed. The faulty interpretation of system due to presence of compensatory response (CR) and inverse response (IR) from backward loops and forward paths in the process, have been eliminated. Furthermore, this method also can estimate the state of the unmeasured variables, to explain fault propagation paths and to ascertain origins.

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NOMENCLATURE

Chapter 3

F_o = Inlet mass flow rate (l/s)

C_{ao} = Inlet feed concentration (mol/l)

T_o = Inlet fluid temperature (°C)

V = Volume of reacting solution inside the tank (l)

T = Reacting solution temperature (°C)

C_a = Reacting solution concentration (mol/l)

F = Output mass flow rate (l/s)

V_j = Volume of the jacket (l)

F_j = mass flow rate of coolant (l/s)

T_{jo} = Inlet temperature of coolant (°C)

T_j = Outle temperature of coolant (°C)

k = Specific rate constant

n = Order of reaction

U = Overall heat transfer co-efficient (W/m^2°C)

A = Area of heat transfer between tank and jacket (m^2)

h = Enthalpy of reacting solution (J/kg)

h_o = Enthalpy of inlet feed (J/kg)

h_{jo} = Enthalpy of inlet coolant (J/kg)

h_j = Enthalpy of outlet coolant (J/kg)

K_v = Controller gain

ρ = Density (kg/m^3)

ρ_j = Density of coolant (kg/m^3)

Chapter 4

N = Number of trays

i = Used to refer a particular number

L = Liquid flow rate from trays (l/s)

F_f = Feed flow rate (l/s)

F_d = Distillate flow rate (l/s)

F_{rd} = Reflux flow rate (l/s)

F_b = Bottom product flow rate (l/s)

V = Molal vapor flow rate (mol/s)

M = Liquid hold-up on trays (l)

M_{rd} = Reflux drum hold-up (l)

M_b = Column bottom hold-up (l)

x = Mole fraction of more volatile component in liquid phase

y = Mole fraction of more volatile component in vapour phase

x_f = Mole fraction of more volatile component in feed

x_d = Mole fraction of more volatile component in distillate

x_b = Mole fraction of more volatile component in bottom product

y_b = Mole fraction of more volatile component in vapor phase at column bottom

α = Relative volatility

Chapter 5

M_f = Mass flow rate of water into drum (kg/s)

M_s = Mass flow rate of steam from drum to outside (kg/s)

P = Pressure inside the drum (Pa)

l = Drum level (m)

V_{st} = Total volume of steam (m^3)

V_{wt} = Total volume of water (m^3)

V_{sd} = Volume of steam in the drum

V_{wd} = Volume of water in the drum

Q = Amount of heat irradiated (J)

h_f = Enthalpy of feed water (J/kg)

h_s = Enthalpy of steam (J/kg)

ρ_s = Density of steam (kg/m^3)

ρ_w = Density of water (kg/m^3)

V_r = Volume of the riser (m^3)

α_r = Mass fraction of steam

α_v = Volume fraction of steam

q_{dc} = Mass flow rate through the downcomer (kg/s)

q_r = Mass flow rate through the riser (kg/s)

m_t = Mass of metal (kg)

C_p = Specific heat capacity (J/kg°C)

t_m = Average change in temperature of metal (°C)

t_s = Change in temperature of metal in riser (°C)

L_r = Length of riser section (m)

L_{dc} = Length of downcomer section (m)

g = Acceleration due to gravity (m/s^2)

K = Coefficient for frictional loss

A_{dc} = Cross-sectional area of downcomer (m^2)

A_d = Area of drum (m^2)