PROCESS FAULT ANALYSIS USING SIGNED DIRECTED GRAPHS AND FUZZY LOGIC

A PROJECT REPORT SUBMITTED IN THE PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF

Bachelor of Technology

in

CHEMICAL ENGINEERING

by

KOTHA PRUTHVI REDDY

109CH0353

Department of Chemical Engineering

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Under the guidance of

Dr. Madhusree Kundu

Department of Chemical Engineering
National Institute of Technology
Rourkela

National Institute of Technology, Rourkela

CERTIFICATE

This is to certify that the thesis entitled **"PROCESS FAULT ANALYSIS USING SIGNED DIRECTED GRAPHS AND FUZZY LOGIC"** submitted by Kotha Pruthvi Reddy in the partial fulfillment of the requirement for the award of BACHELOR OF TECHNOLOGY Degree in Chemical Engineering at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance.

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

Date:

Dr. Madhusree Kundu
Department of Chemical Engineering
National Institute of Technology
Rourkela - 769008

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Place:

Date:

Kotha Pruthvi Reddy

Roll No: 109CH0353

Department of Chemical Engineering

NIT, Rourkela

Rourkela-769008

ABSTRACT:

Now-a-days in modern industries, the scale and complexity of many systems are increased continuously. These systems are subjected to low productivity, system failures because of mis-operation, external disturbance or sometimes control system failure which often gets out of control and leads to huge destruction in terms of infrastructure and personnel. When a fault is detected the next steps to follow are identifying the root cause of the fault, determining the extent to which the system functioning can be maintained despite of the fault and to find a suitable solution or repair to the fault. Hence at present, fault diagnosis is required for a large and complex system of industrial processes. Compared with the classic fault detection of local systems, the fault detection for complex systems concern more about the fault propagation in the process systems. This demand is much close to hazard analysis which is a kind of qualitative analysis. Signed Directed Graph (SDG) is a kind qualitative graphical model which can be applied for fault diagnosis. Also in this paper another alternate method for qualitative process modeling which uses fuzzy graph theory based on SDG known as Fuzzy-SDG to qualitatively represent the process systems. SDG and Fuzzy- SDG has been applied to various systems in this paper and their effectiveness was observed.

Various systems that have been studied are: Feed Back Control system, Cascade control system, Dual averaging control system and three element control system. Using the working principle of each process and theoretical knowledge, SDG was developed for each process. Also Fuzzy Signed basics were also studied. The main advantage of linking fuzzy logic with the signed directed graph is that it will give more efficient way of resolution of fault diagnosis in process industries.

Key words: Signed Directed graph, control systems, Fuzzy signed directed graph, boiler drum.

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Chapter – 01

INTRODUCTION

1.1 FAULT DIAGNOSIS IN PROCESS INDUSTRIES:

The detection and diagnosis of faults during process operation, as well as assessment of potential hazards and operability problems in the early stage of design are now becoming important factors ensuring good performance but are becoming more difficult because of greater plant complexity and greater degree of plant integration. In many cases, the difficulties arise from analyzing the qualitative features of real time dynamic data. It is of utmost importance that faults are detected early and proper steps are taken to repair or fix that problem so that no harm can be done for the workers or to the machinery of the industries.

Faults are generally categorized into three different types of categories. They are **"sensor fault", "actuator fault"** and **"process fault".**

Sensor Fault: If the measured variable is different from the actual variable, then it is known as Sensor Fault.

Actuator Fault: Actuator is the one which actually carries the complete operation and provides the final output. If there is any error or discrepancy in the command given to the actuator and output, then it is termed as Actuator fault.

Process Fault: Process faults are the other faults of the process system which are additive or multiplicative. Additive faults are like a damage or leakage in the tank and multiplicative faults are like fouling of heat exchanger surfaces etc.

Recent technologies like fuzzy logic signal processing and many others contribute to the development of **Fault detection and diagnosis (FDD)** techniques. For FDD, two types of methods can be used. They are model base method and model free method.

Model Base methods use a mathematically developed model of the process to estimate the exact values of process variables.

Model free methods do not use a mathematical model and this method finds the faults using some predefined laws and theories.

Faults can be further classified into abrupt faults and incipient faults. Abrupt faults are those which are known as sudden faults and these kinds of faults are very dangerous. Incipient faults are slowly developing faults and these kinds of faults will develop over a period of time like fouling on surfaces of heat exchanger or rusting of iron.

Also in order to find the fault using model based method different types of models are available and the model which we selects plays a key role in the identification and isolation of the faults. Different kinds of models which we can use are:

a) **Modeling by Mathematical Expressions** :

If we have differential algebraic equations of the process system , then it is easy to derive the structure and the sign of the graphs from specific methods. In general a typical dynamic process system can be expressed as differential equations

$$dx_i/dt = fi(x_1, \ldots.. x_n)$$

Where $x_1 \ldots x_n$ are state variables.

b) **Modeling by qualitative process knowledge**:

In many cases, the faults are detected by using the process knowledge and experience. The main steps to be done while solving using this kind of models is (1) collect process knowledge, experiment data, statistics and other equations related to the process. (2) Choose the key variables and give proper signs so that how these variables affect the process.

There are also different kinds of modeling like hierarchical modeling where the entire process is divided into three levels and then it is solved for detecting the faults. But the above two types of modeling are common and in this paper we have used these two models to detect the faults in the process systems.

Signed Directed graph method is used as mode for the detection of fault in process industries. It is a kind of qualitative graphical models to describe the process variables and their cause effect relations in continuous systems denoting the process variables as nodes.

Fuzzy signed directed graphs are also used. It uses fuzzy set in conjunction with graph theory. The advantages of such type of description are it uses some knowledge of process principles but it did not need to solve the problems through simulation because of having ability to model the process topology and it can give a picture of cause effect relationship between the variables. The key features of Fuzzy logic tool box are

(i) Specialized GUIs for building fuzzy inference systems and viewing and analyzing results
(ii) It is easy to develop membership functions for creating fuzzy inference systems
(iii) Support for AND, OR and NOT logic in user defined rules.
(iv) Its ability to develop Standard Sugeno and Mamdani type fuzzy inference systems.

Chapter – 02

LITERATURE REVIEW

2.1 SIGNED DIRECTED GRAPH BASED FAULT DIAGNOSIS:

In general, SDG is a representation of process casual information, in which process variables are represented as nodes and the relationships between the process variables are denoted as directed arcs or simply arcs. Process variables are in general are those variables which are key variables in the process and those variables which gets effected by the faults in the system like temperature, pressure, flow rate etc. The nodes in the SDG include “0”, “+”, “-” which represents the normal steady state value and higher and lower steady state values respectively. The Directed arc or Arc points from a cause node to its effect node. The arc pointing from cause node to its effect node may be a positive arc which is a solid line or it may be a negative arc which is a dotted line. The line being positive or negative depends on whether the cause and effect change in the same direction or opposite direction respectively. In general, the sign of a positive arc is “+” and that of a negative arc is “-”. A simple SDG model is as shown in Figure 1.

Figure 1: A simple SDG model

In the above figure, A is known as cause node and B is known as effect node and the arc between them being solid, the cause and effect change in the same direction. Here in order to detect the fault or to conduct the fault diagnosis, another kind of node called reason node is used which is shown in rectangle shape. This node is responsible for all abnormal reasons which cause variations in its adjacent node. Another term **Consistency** is used for the arcs which means that an arc is said to be consistent if and only if sign of cause node *sign of effect node *sign of effect = +. The reason node will have at least one consistent arc connecting it to an effect node and no such type of consistent arc to a cause node. If a path is considered as consistent, then it must have all reason nodes, effect nodes and consistent arcs.

2.1.1 SDG BASED MODELING KNOWLEDGE ON CONTROL LOOPS:

In many chemical processes, there are many control loops which keeps the controlled variables at its normal ranges. So, when a fault occurs, control loops generally protect or mislead the real causes. So hence it is very important to do the SDG modeling for control loops with utmost care.

Here a tank level control system is taken as an example. It is shown below in Figure 2.

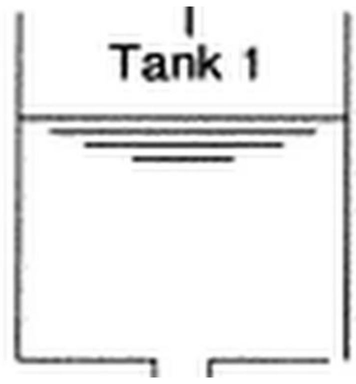

Figure 2: Simple water tank system

The SDG of the tank level control system is shown in Figure 3. In the Fig, L_m represents the measuring value of the tank level and LV represents the set point of the level and L_{SP} is valve. The output flow rate is denoted by F.

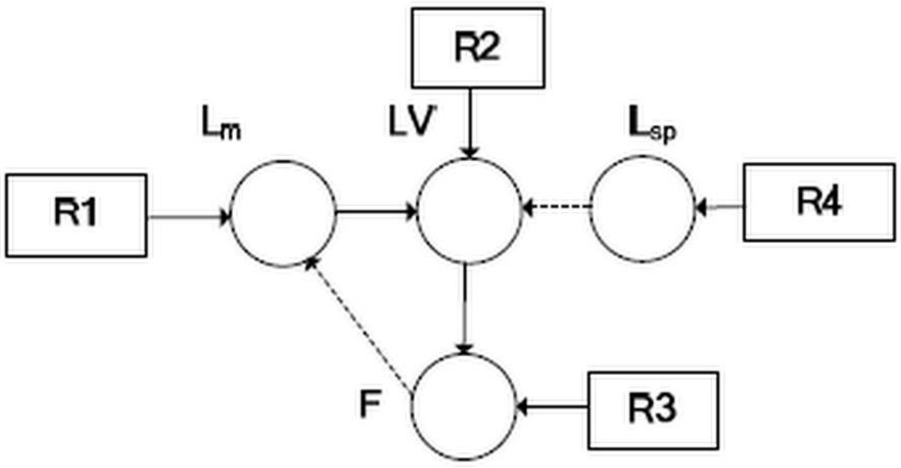

Figure 3: SDG of simple water tank level control system

All the abnormal reasons are considered in reason nodes and all other faults in the control loop are modeled such as valve bias, controller failure which is shown in Table 1.

Table 1: Faults in Reason nodes

	Reason nodes			
	R1	*R2*	*R3*	*R4*
Faults	Sensor bias; Equipment malfunction(eg. leakage, etc)	Valve bias or blocked; Controller failure	Sensor bias	Set point bias

<u>2.2 BIDIRECTIONAL INFERENCE</u>:

Bidirectional inference is an algorithm used to combine both the forward inverse inferences. This inference is used to overcome the influence of control loop on the controlled variables as it is the main problem which actually happens in many process industries. The algorithm for the Bidirectional inference is as follows:

(1) The node which alarms initially is kept in a stack and it is considered as current node. From current node inverse inference on the SDG through its cause node is carried out.

(2) A node is marked as current node when the arc from cause node to current node is said to be consistent. Then this cause node is denoted as

current node and again it is put back into the stack as a current node. This inference is carried out till the reason node is found out for the current node.

(3) In the above step if the arc is not consistent, then the cause node will be observed whether the node is in steady state or the node is the controlled variable. It is also observed whether the operating variable has been on the consistent path. It is also to be observed whether the control loop is influencing the cause node. If it is found to be correct it means that fault has been propagated through the cause node, but the control loop kept the cause node in its normal state through its control action. It keeps the controlled variable normal by making the suitable changes in operating variable. To find the real root cause, the state of cause node is to be marked as "+"or "-" making the arc consistent. Then again go for previous step.

(4) From the reason node found out in the previous step, forward inference is carried out from the previous node on the path to the abnormal nodes in the SDG model to predict the states of them. It is just a process of validation. If the control loops influence the controlled variable, during the forward inference, if the controlled variable is normal, its state is supposed to be abnormal. It is assumed to be right if and only if the states of the abnormal nodes are same with the states predicted.

(5) If there are abnormal nodes being unsearched, then we have to go for Step no 2, otherwise stop or end the algorithm.

After the above five steps, we will have all the possible causes and the consistent paths and hence this algorithm will ensure its completeness.

In order to develop a SDG, basic knowledge regarding the Digraphs is required. Hence a case study on Digrpahs has been studied as a part of literature review.

2.3 CONTROL LOOPS:

In general control loops present in each and every process in which the essential components are sensor, controller and control device. Through SDGs the two different types of basic control loops are

a) **Negative feedback control loop:** Any moderate deviations which occur in the variables are corrected through this loop. In these loops digraphs start and end at the same node. It measures the difference between the set point and output and hence controls the output by comparing it with the desired value through tis control action.

b) **Negative feed forward control loop:** As per the theory, any disturbance created through this loop will cancel out, but this is not practically possible. It measures the load output directly and hence controls the output.

In general, negative loops play a key role in many process industries, because they will stabilize the system. In a positive loop disturbance in one particular direction will lead to the same disturbance in all other variables and the fault keeps on multiplying. Hence it is better to have as many numbers of negative loops as that of positive loops.

Here we have considered an example of a water tank system, courtesy literature review and through this example the concept of digraph was studied.

2.4 WATER TANK SYSTEM:

The Schematic diagram of water tank is clearly shown in Figure 4.

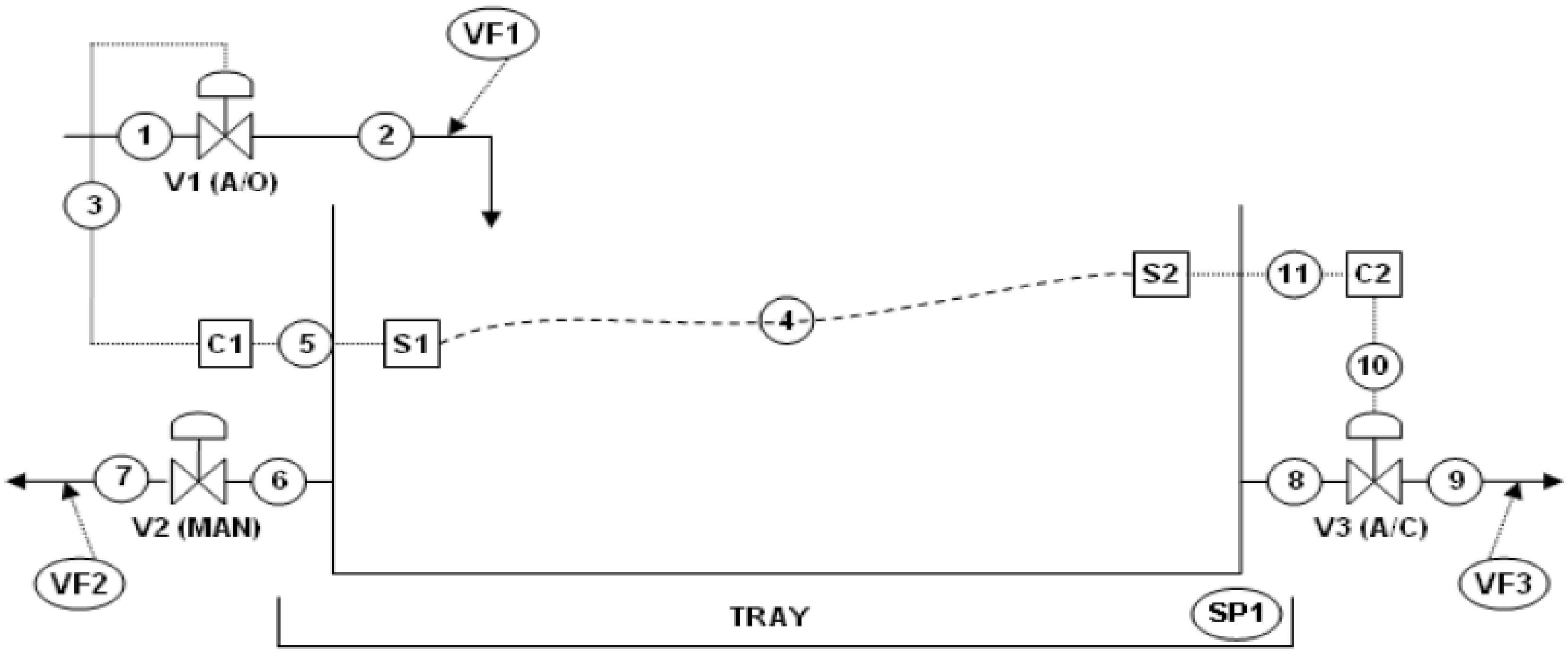

Figure 4: Schematic Diagram of Water tank system

The main of this system is to maintain the level of water between the pre-determined levels. Sensor (S1) is used to monitor the level of water level in the tank. Under steady state conditions, water flows in through valve1 (V1) and flows out through valve2 (V2). If there is any leakage or overflow through the tank, the water is collected through the tray as shown in the Fig 4.

2.4.1 DETAILS OF THE SYSTEM:

The system comprises of three valves V1, V2 and V3, two level sensors S1, S2, two controllers C1, C2 and a spill tray to collect the water which comes out of the tank through any kind of leakage or overflow. Sensor S1 monitors the level of water in the tank and it sends the signal to the controller C1 which in turn controls the valve V1 to control the flow rate of water through V1. It is maintained in such a way that if the level of the water is more than the desired level the controller C1 sends a command to the valve to shut down the supply so that water is drained out and hence maintains the desired level inside the tank and vice versa. V2 is not associated with any controller since it is operated manually. In steady state or normal conditions valve V3 is kept closed as it is considered as a safety valve. If in any case if the controller C1 fails give command to Valve V1 to operate, then sensor S1 senses the level of water and sends the signal to controller C2 which in turn sends the command to valve V3 which makes the V3 open and let the excess water out. If there is any excess water flow in the tank then water will overflow from the tank and gets collected in the tray provided. The flow sensors will measure the flow rates through the respective valves. Another sensor SP1 is provided in the tray to detect whether there is an overflow in the tank.

There are two operating modes for the system. They are

a) **Active Mode:** In this mode the valves V1 and V2 are kept open and V3 is closed.
b) **Dormant Mode:** The system is said to be dormant when all the valves are kept closed.

2.4.2 STEPS FOR DEVELOPING DIGRAPH:

(1) Clearly define the system to be analyzed
(2) Listing out the all possible component failures.
(3) The system is divided into sub units and components.
(4) All control loops present in the system are to be identified.

(5) Digraphs of the individual sub units are to be found out by taking into the consideration all process variable deviations which could have an effect on the variables present in the model.

(6) All the digraphs of sub systems are connected to form the entire digraph of the whole system.

(7) Through Back tracing all the possible faults are found out.

2.4.3 ASSUMPTIONS:

The following assumptions are made while constructing the digraph for the water tank system.

(1) If there is any kind of pipe rupture, flow sensors could not detect it.

(2) The system is in steady state initially

(3) A rupture in the tank causes more leakage of water than the tank leakage.

2.4.4 WATER TANK DIGRAPH:

Digraphs for the individual sub units are shown in the figures below. Control loops present in the water tank system are represented as negative feedback control loops. They are used since they have the ability to correct any kind of moderate disturbances in any of the process variables.

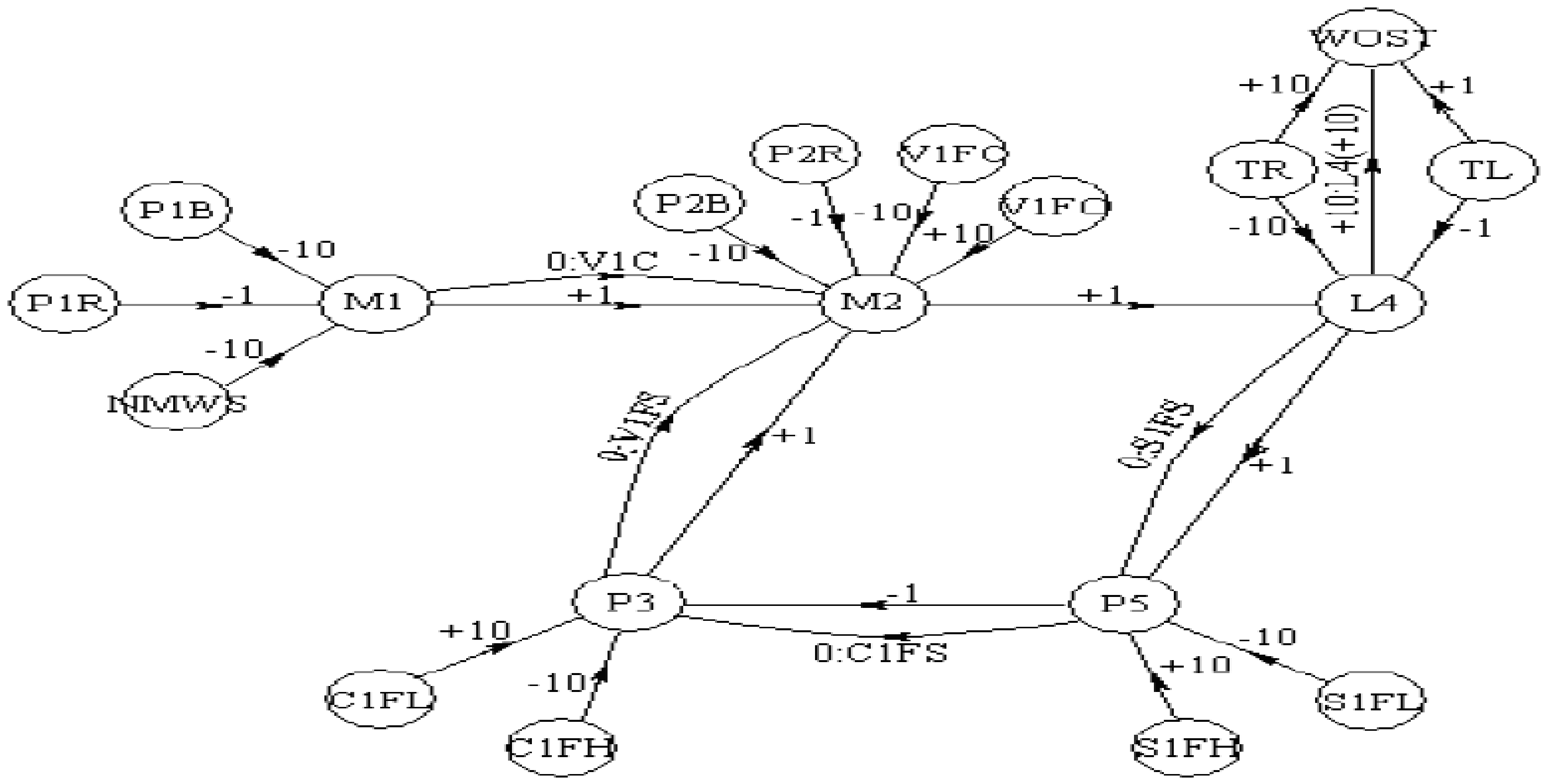

Figure 4: Digraph of control loop one near valve V1

The above Figure illustrates the combined digraph of valve V1 and its respective control loop. The control action of the control loop is represented by the negative feedback loop of M2-L4-P5-P3. Now let us take a look at the different faults and their causes. M1 entering V1 can be affected by three kinds of component failures P1B, P1R all of which decrease the mass flow. M2 can be affected by four components of failures. P2B, P2R and V1FC decrease the mass flow rate of M2 whereas V1FO increase the mass flow rate of M2. If M2 decreases for some reason then just reverse action will takes place and liquid level will be adjusted accordingly that is it becomes higher. Similarly based on logical reasoning, other nodes can be studied and they are interlinked with each other to obtain the final digraph. The digraph for the manual valve V2 is shown in Figure 5:

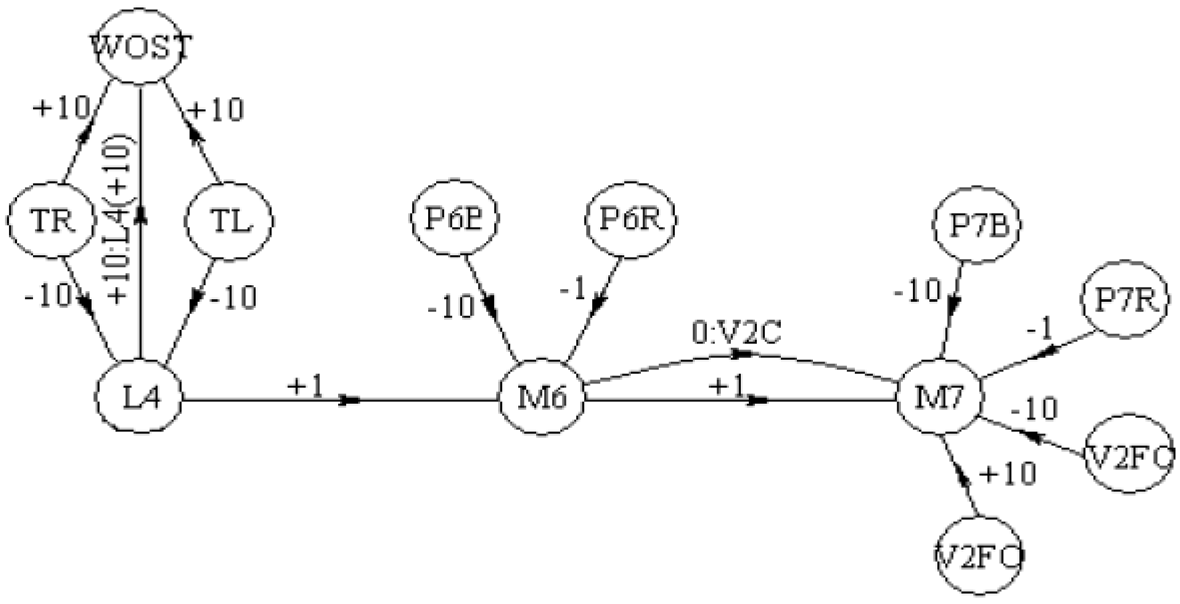

Figure 5: Digraph of manually operated valve V2

In the above figure different failures affecting the components of M6 and M7 are shown. An increase in L4 increases in M6 which in turn increases in M7.

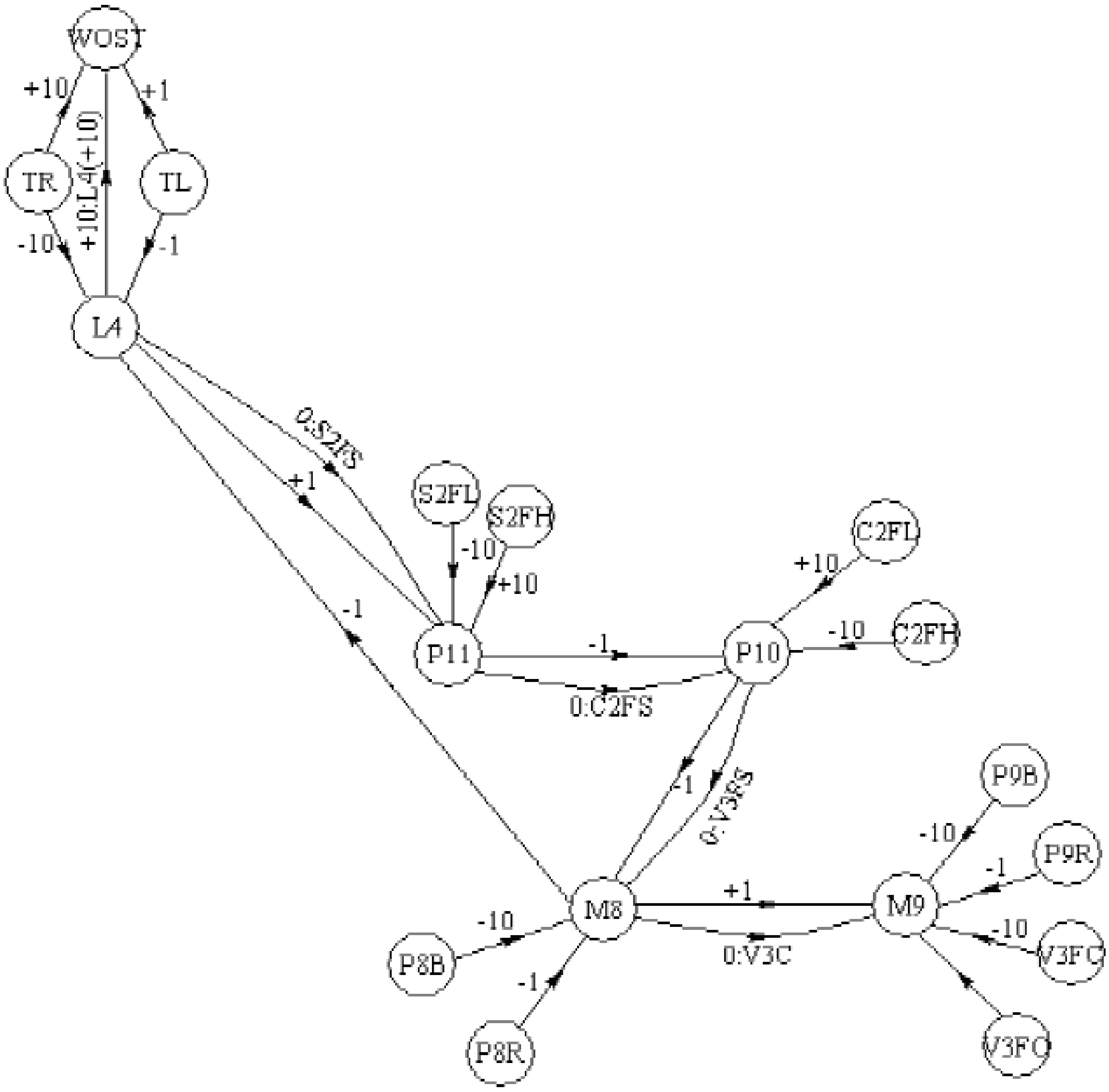

Figure 6: Digraph of control loop two near valve V3

The above figure gives the air to close V3 through the relationship between the M8, M9 and P10. As V3 is air to close valve, low pressure opens the valve and flow increases giving high M8 and M9.

The complete digraph is obtained and is shown in Figure 7 by combining the Figure 4, Figure 5 and Figure 6.

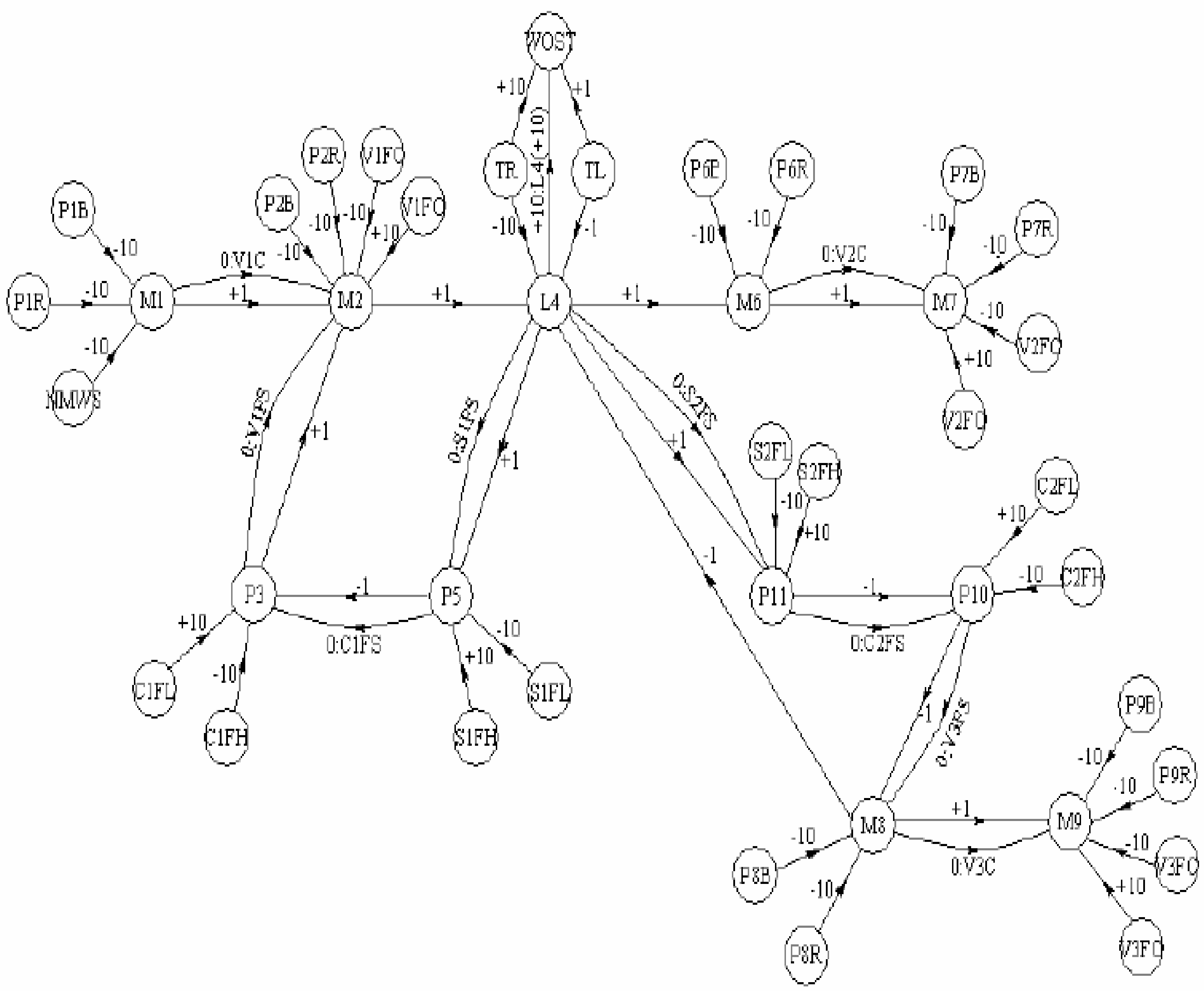

Figure 7: SDG of the entire water tank system

2.4.5 FAULT DIAGNOSTIC METHODS:

For fault diagnosis, the system sensor readings are compared with the expected values when the system is in operating mode. If at all 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 in two ways.

Method one: Back tracing is done from the fault node until the point where there is no further back tracing can be done. The main disadvantage associated with this is many faults will be generated and most of them seems to be contradictory and hence creates an ambiguity.

Method two: From sensor readings it is observed that which particular areas is showing deviation and that particular area is flagged off leaving behind the non-deviating nodes. Back tracing from a node stops as soon as it reaches the boundary of the flagged section.

Let us consider an example of method two. A deviation from the normal active mode in which VF1 and VF2 showing no flow of water through the valves. Since there is no problem with VF3 or SP1, this particular section can be flagged off. No flow in V1 will cause M2 to decrease which can be caused by P2B, P2R and V1FC. It will also be caused by a decrease in M1 which in turn caused by P1R, P1B. If we go through the control loop, decrease in M2 will also be registered due to high liquid level through L4.

Following chapters are based on the control systems and water tank problems that have been studied as a part of this project and their SDGs and Fuzzy SDG are developed.

Chapter – 03

FEEDBACK CONTROL SYSTEM

3.1 CONTROL SYSTEMS:

Control systems often play a very important role in many chemical processing industries. The main aim of these control systems in industries is to control the process variables such as temperature, pressure, flow rate etc. Control actions should be considered particularly because they are the forced actions which are different from the process itself and they are responsible for misleading of the fault propagation. Here in this chapter different types of control systems are considered and their SDGs are developed with the help of the existing theoretical and process knowledge.

3.2 FEED BACK CONTROL SYSTEM:

Feed Back Control systems play a very important role in process control system industries. Typical feedback control system is shown in Fig 9. In feedback control systems the variable which is to be controlled is measured and it is compared with the desired value. The difference between the actual value and the desired set point is called error. Feedback control system tries to reduce the error by adjusting or manipulating the input value to the system.

3.2.1 SYSTEM DESCRIPTION:

In the below figure,

r = desired set point

e = error

u = controller output

x = controlled variable

q = manipulated variable

x_m = measurement of final controlled output

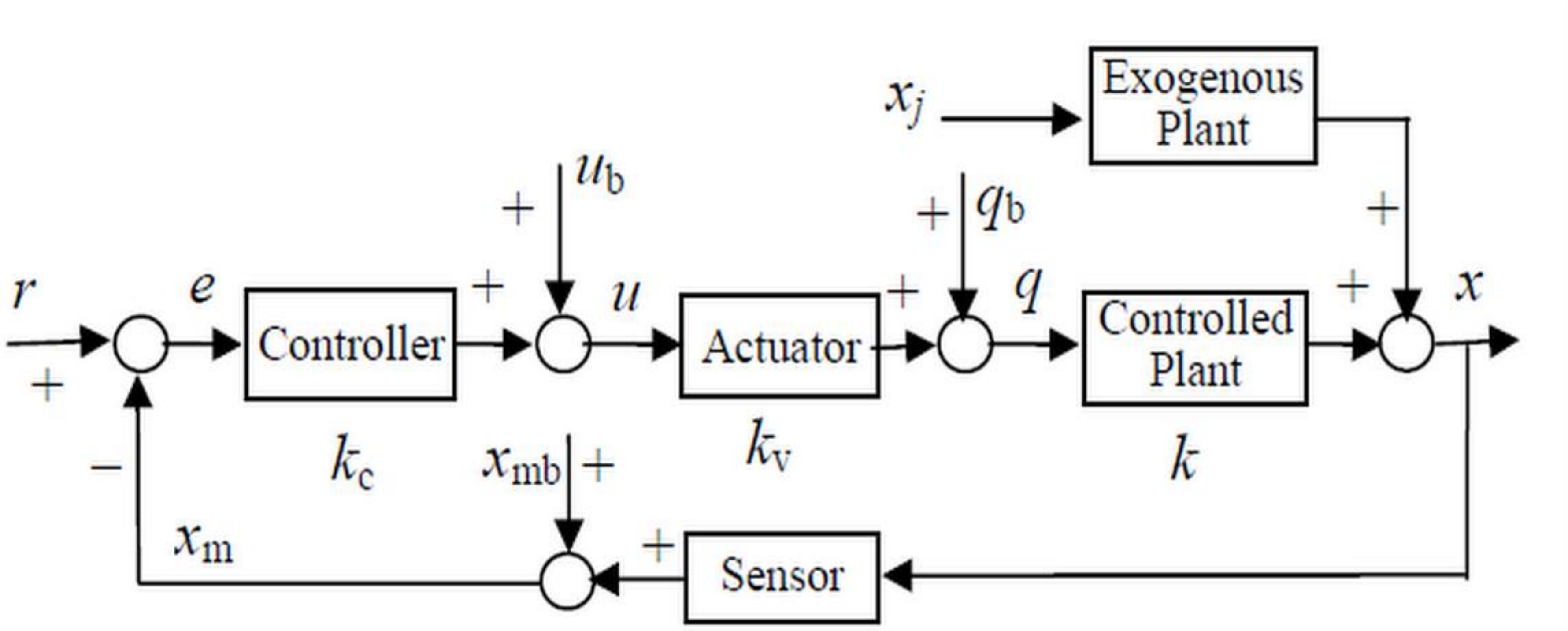

Figure 8: Block diagram of Feed Back control System

u_b, q_b and x_{mb} are the respective bias of the control elements. Here the error "e" of the set point r and the final controlled output x_m is inputted through the controller. It is assumed that the controller is a PID controller. Then the output of the PID controller "u" goes to the control element whose output is a manipulated variable "q". The manipulated variable enters into the process element and gives the controlled variable output "x". The output variable is measured using a sensor which is shown in the figure and it is compared with the set point "r" which finally gives the error. The aim of the feedback control system here is to reduce that error by adjusting the input. But in many control systems what happens is that the control system influences the controlled variable which leads to the truncation or misleading of the fault propagation path. So in order to find the fault propagation path in such cases here a new algorithm is found and hence the signed directed graph is also drawn to find the fault propagation path in such kind of control systems.

The algorithm is as follows:

(1) From the existing theoretical knowledge we need to develop a block diagram and then all the equations associated with the control system are to be found out.

(2) Relations between the variables needs to be found out such that whether a change in variable causes positive, negative or neutral effect on the adjacent or related variable.

(3) Then the Signed Directed Graph is drawn basing on the process knowledge and the fault propagation path is found out by using the equations and process knowledge and with logical reasoning.

By using the control law of the feedback control system, the various equations involved are:

$$\mathbf{x_m = x + x_{mb}} \quad (1)$$

$$\mathbf{e = r - x_m} \quad (2)$$

$$\mathbf{u_p = k_c e} \quad (3)$$

$$\mathbf{(d/dt)u_I = k_c e/\tau_I} \quad (4)$$

$$\mathbf{u_D = kc\tau_D(de/dt)} \quad (5)$$

$$\mathbf{u = u_{p+} u_I + u_D + u_b} \quad (6)$$

$$\mathbf{q = k_v u + q_b} \quad (7)$$

$$\mathbf{x = kq + a_j x_j} \quad (8)$$

Here $\mathbf{a_j}$ and $\mathbf{x_j}$ are the additional gain and external disturbance of the exogenous plant as shown in the figure above. $\boldsymbol{\tau_I}$ and $\boldsymbol{\tau_D}$ are the integral and differential time constant respectively. Basing on the above equations the relationship the variables can be found out whether a positive or negative or neutral effect is existing between the variables which are connected through the equations. Table 2 shows the perfectly matching variables using the above equations.

Table 2: Matched variables

Equation	Variables with "+"cause and effect
1	x_{mb} and x
2	e and x_m
3	u_p and e
5	u_d and u_d
6	u and u_p
7	q and u
8	x and q

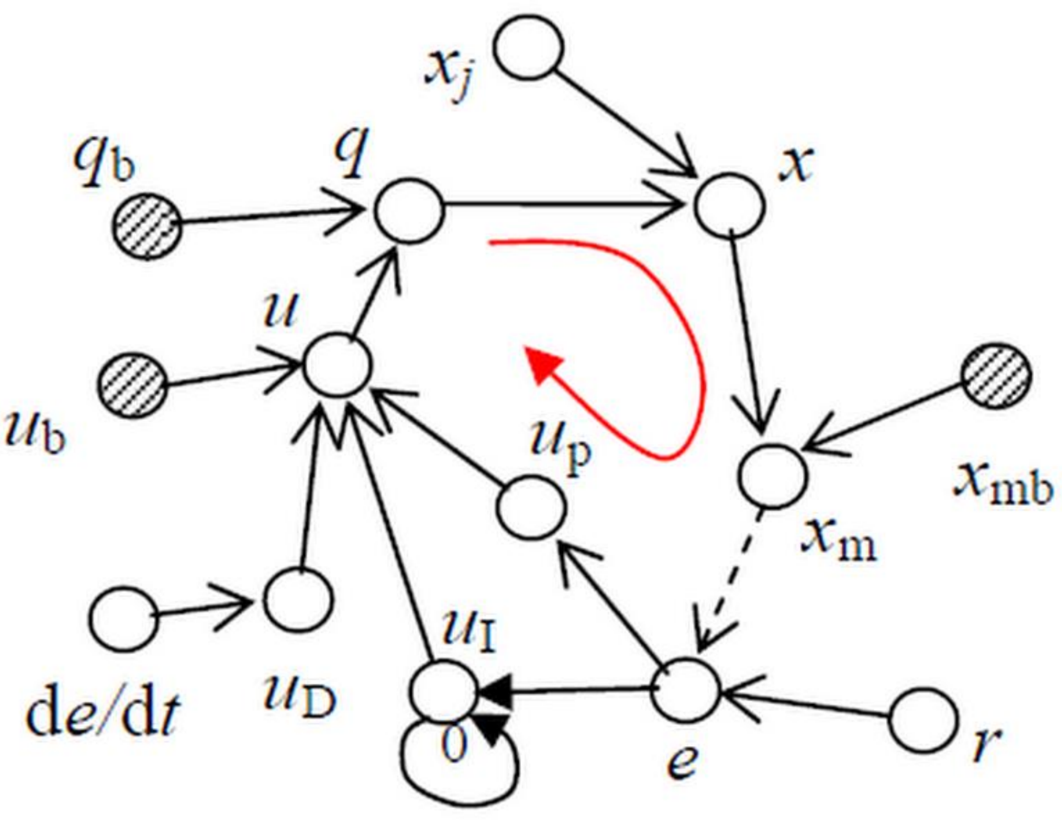

Figure 9: SDG of the system

In the above SDG shown the nodes which are denoted with dotted lines are deviation nodes and the arrows with solid line represent the positive effect the variables and the arrows with the dotted line represents the negative effect present between the variables. Since we have considered that the controller is a PID controller u_p, u_I and u_D are drawn as three separate nodes because their effect changes with respect to time. We can also say that the above SDG is drawn considering the initial response of the system. That is the reason why u_I is marked with "0", since during the initial response the integral controller will not have that much effect. Hence its effect is considered to be negligible. Also the effect of de/dt is considered as a node because of its special effect on u_D. But its effect is limited to only during the initial response itself. Using the above SDG, the initial response can be analyzed. If the set point **r** is decreased then the corresponding nodes **e**, $\mathbf{u_p}$, **u**, **q**, $\mathbf{x_m}$ and **x** will have the same positive effect and these nodes will also show a decrease in their corresponding measurement and the corresponding value of $\mathbf{u_I}$ will decrease immediately because there is a direct arc connecting from **e** to $\mathbf{u_I}$. Also it is found that the propagation path is consistent. So after finding SDG what we can infer form here is that the fault propagation path of the initial response of the feedback control system is the longest acyclic path, in which fault origination path will start from its desires set point. The actual fault propagation path will be **"set point → error → manipulated variable → controlled output → measured value → error".** Also it is found that the path is consistent.

In steady state the value of error is zero in the final response. Since the value of error "e = 0" in this case, both the values of u_p and u_D are zero. In order to form SDG again we need to develop the differential algebraic equations by using the process knowledge and logical reasoning. The above DAE's will change and the new equations are as follows:

$$\mathbf{x_m = x + x_{mb}} \quad (9)$$

$$\mathbf{x_m = r} \quad (10)$$

$$\mathbf{u = u_I + ub} \quad (11)$$

$$\mathbf{q = k_v u + q_b} \quad (12)$$

$$\mathbf{x = kq + a_j x_j} \quad (13)$$

From the above equations we can easily find the relationship between the process variables and these are tabulated in Table 2. After forming the tables it is easy to draw the SDG and then fault propagation paths are found out.

Table 3: Matched variables when system is at steady state

Equation	Variables with "+" cause and effect
(9)	$\mathbf{x_m}$ and **x**
(10)	**r** and $\mathbf{x_m}$
(11)	**u** and $\mathbf{u_I}$
(12)	**q** and **u**
(13)	**x** and **q**

From the above table we can easily draw the SDG of the system and it is shown in Figure 10 as follows:

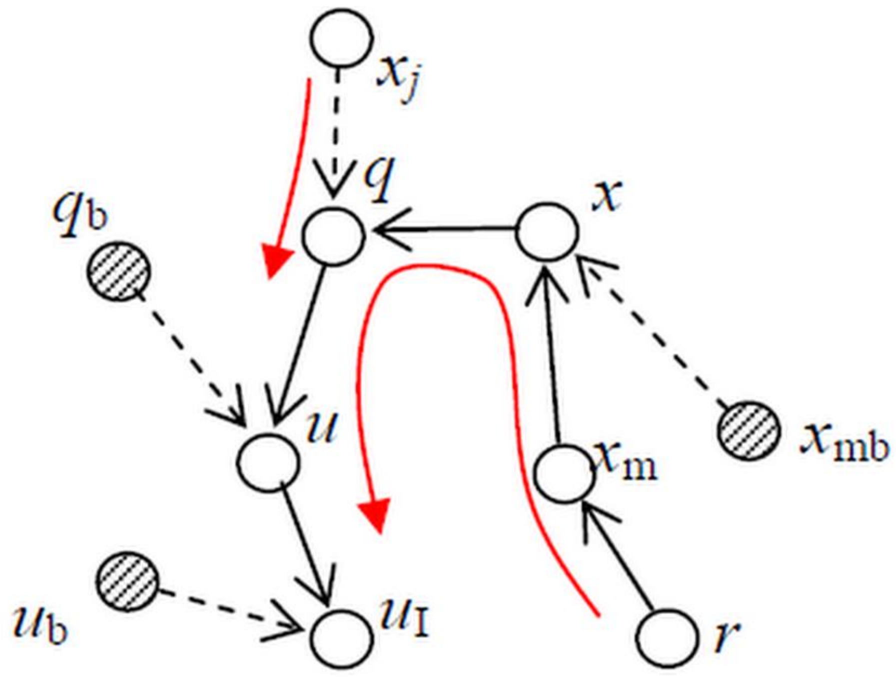

Figure 10: SDG of the steady state system

3.2.2 FAULT PROPAGATION PATH:

In the above figure it is clear that there are two fault propagation paths.

They are (i) $\mathbf{r \rightarrow x_m \rightarrow x \rightarrow q}$

(ii) $\mathbf{x_j \rightarrow q \rightarrow u \rightarrow u_I}$ Here if there is any change in the value of set point, let us say if there is a decrease in the value of set point, then the corresponding nodes $\mathbf{x_m}$, **x**, **q**, **u** and $\mathbf{u_I}$ will register the same response it means they will also decrease accordingly. However if there is an increase or decrease in $\mathbf{x_{mb}}$, then the value of $\mathbf{x_m}$ will not get effected but there will be an increase or decrease in the value of x respectively. This is the influence of control action on the loop. From here what we can infer is that, when a control loop is undergoing some operation or processing, then the controlled variable is determined by the set point and the controller seems like an amplifier with an infinite gain. It is a typical controller in which inputs are zero and the output is determined according to the demand. Also the action of D controller on the loop is limited to only in the initial stages and hence it is removed in the final steady state loop similar is the case for P controller also. Because of I action some variables will show compensatory response in the initial stages. For example the node x_{mb} will tries to limit the response of x_m in the initial stages. Also the fault propagation path in this case is exactly opposite as that of the initial response case. So we can finally conclude this study with two cases. They are (i) When control loop operates then the fault propagation will be due to the deviation of sensor, or other external disturbances.

(ii) When control loop does not operate we will have two cases through which fault may propagate. They are (1) structural faults (2) excessive deviation which causes the controller saturation which automatically leads to the error = zero.

Chapter – 04

CASCADE CONTROL SYSTEM

4.1 INTRODUCTION:

Cascade Control system can be considered as an extension of a single loop control. The main advantage of cascade control system is that it will improve the performance of control system over a single loop control whenever either the measurable intermediate value is getting affected by the disturbances or when the primary process output that we needs to control gets directly affected by the secondary process output. In this case cascade control system can limit the effect of disturbances entering into the secondary variable on the primary output. The main application of cascade control systems is seen in case of shell and tube heat exchangers.

4.1.1 SYSTEM DESCRIPTION:

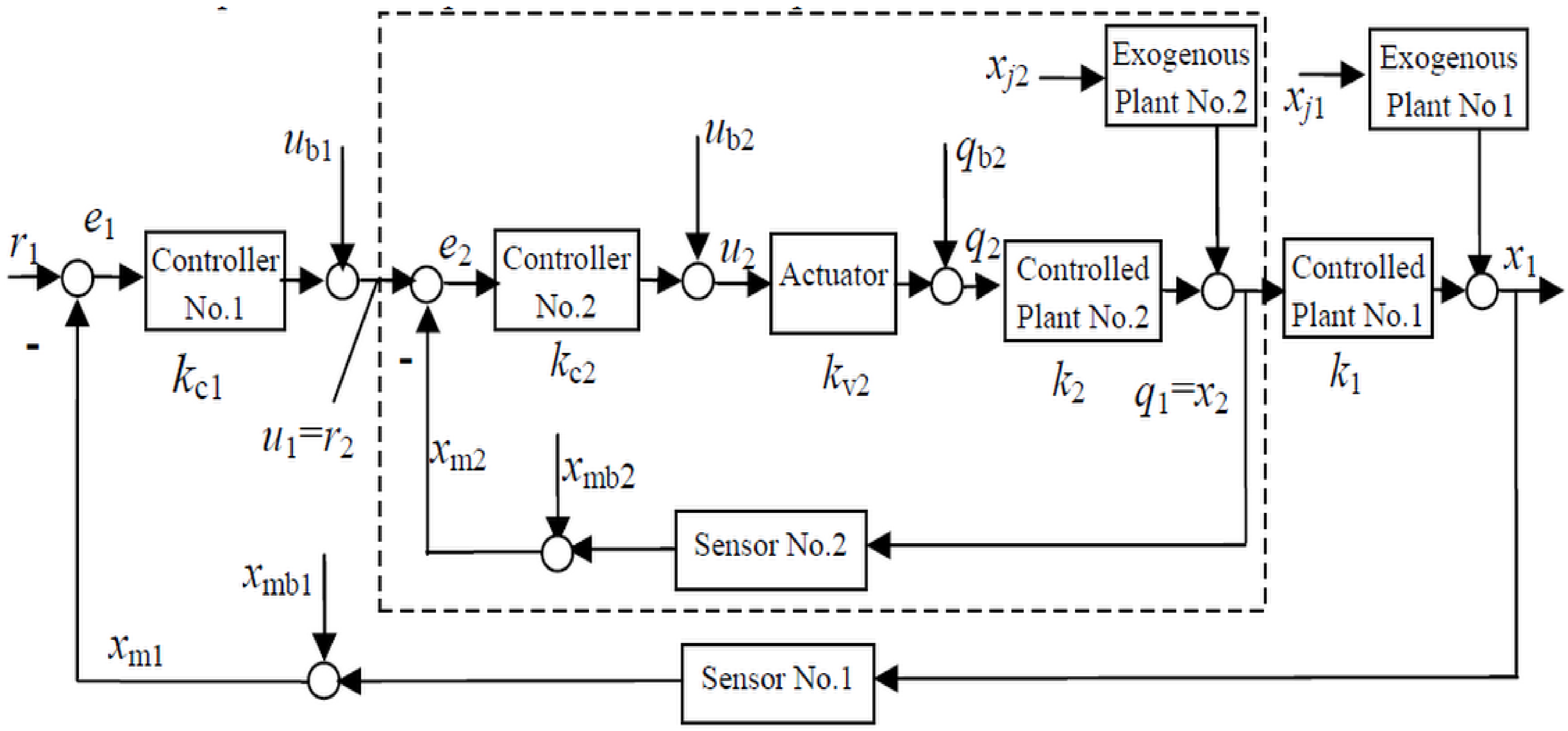

Figure 11: Block Diagram of Cascade Control System

In the above figure we have two loops in which $\mathbf{e_1}$ is the error of the outer loop and $\mathbf{e_2}$ is the error in the inner loop and all other variables are given same meaning as that in the previous case of feedback control system. To construct SDG we need to follow the same algorithm as said before. In order to form SDG again we need to form all the equations by using the process knowledge.

Equations related to the above cascade control system are clearly given below. The different equations involved here are:

$$x_{m1} = x_1 + x_{mb1} \qquad (14)$$

$$e_1 = r_1 - x_{m1} \qquad (15)$$

$$u_{p1} = k_{c1} e_1 \qquad (16)$$

$$q_1 = k_{v1} u_1 + q_{b1} \qquad (17)$$

$$(d/dt)u_{I1} = k_c e_1 / \tau_{I1} \qquad (18)$$

$$u_{D1} = kc\tau_{D1}(de_1/dt) \qquad (19)$$

$$u_1 = u_{p1} + u_{I1} + u_{D1} + u_{b1} \qquad (20)$$

$$x_1 = k_1 q_1 + (a_j x_j)_1 \qquad (21)$$

All the above equations are related to the outer loop and the equations and the equations related to the inner loop will be similar to that of the outer loop. In the construction of SDG another key step is to find the relationship between the variables. Considering the system to be in steady state we found that the relationship between the variables $\mathbf{u_{b2}\text{-}u_{I2}}$, $\mathbf{q_{b2}\text{-}u_{I2}}$, $\mathbf{x_{j2}\text{-}q_2}$, $\mathbf{x_j\text{-}q_{(x2)}}$, $\mathbf{u_b\text{-}u_{I1}}$, $\mathbf{x_{mb}\text{-}x_1}$ is found to be negative. It means that a decrease in one variable will leads to increase in the corresponding variable. Therefore from the above equations and the above relationship it is easy to draw the SDG when the system is at steady state and it is clearly shown in Figure 12.

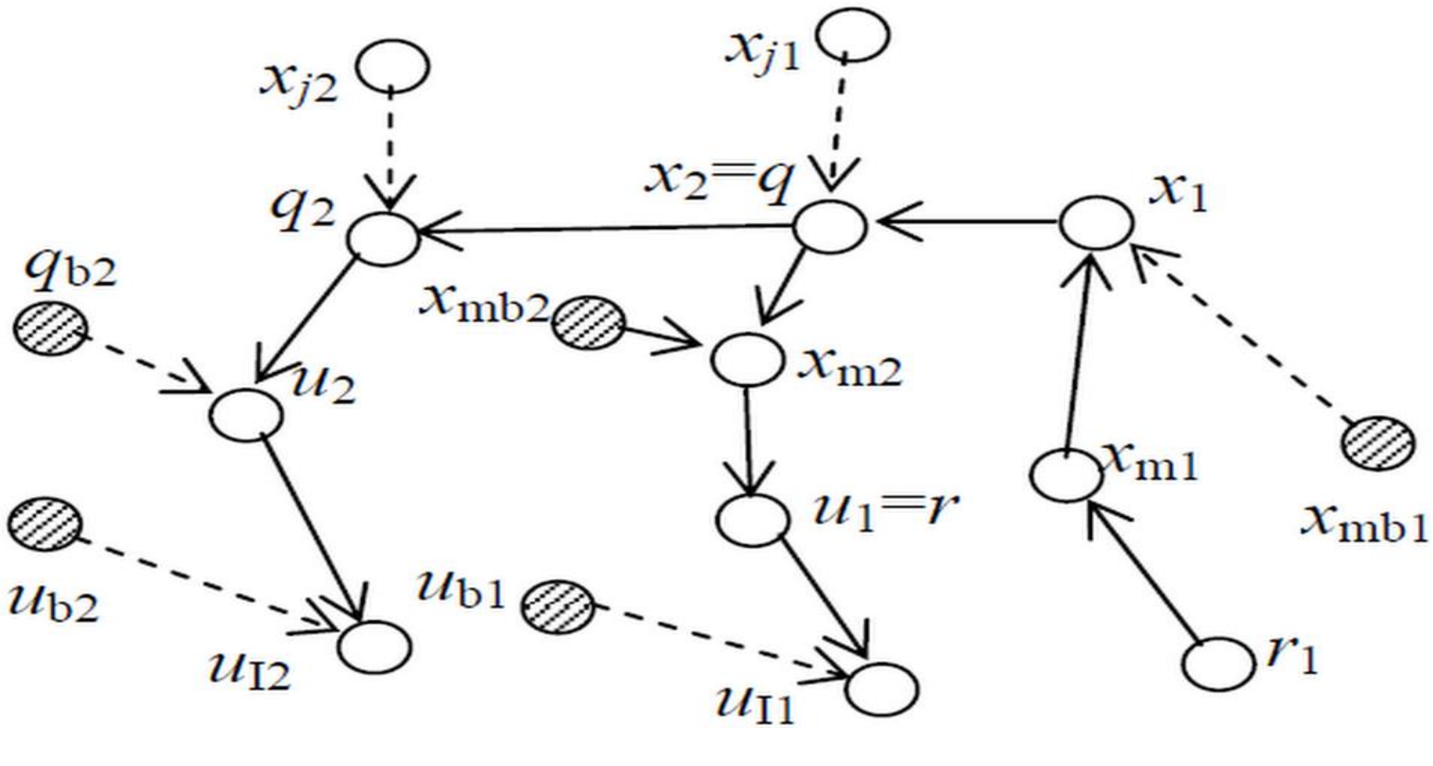

Figure 12: SDG of steady state Cascade control system

4.1.2 FAULT PROPAGATION PATH:

From the above figure what we can infer is that there are three fault propagation paths similar to that of the feedback control system.

They are (i) $\mathbf{r_1 \rightarrow x_{m1} \rightarrow x_1 \rightarrow x_2 \rightarrow x_{m2} \rightarrow u_1 \rightarrow u_{I1}}$

(ii) $\mathbf{x_{j1} \rightarrow x_2 \rightarrow xm_2 \rightarrow r_1 \rightarrow u_{I1}}$

(iii) $\mathbf{x_{j2} \rightarrow q_2 \rightarrow u_2 \rightarrow u_{I2} \dashrightarrow u_{b2}}$

In the above figure the nodes which are marked with dotted lines are deviation nodes. These nodes are based on the bias that produced in the system. Initially a change in the node $\mathbf{x_{mb1}}$ will affect the final measurement output variable $\mathbf{x_{m1}}$. But later, it means when the system is in steady state it is not happening because the control action misleads the fault propagation path. Thus all the propagation paths are successfully found out. If we consider the same system during its initial stage, then the initial response SDG will look similar to that of the SDG except that there won't be any kind of breaking of links between the nodes and another two extra nodes will be there for representing the errors present in the inner and outer loop respectively. The path in the initial response will be opposite to the path of the steady state path. In almost all process industries faults will generally occur when the system is at steady state itself. For us it seems like that the system is in steady state but because of the influence of the control loop it will mislead the path. Hence from now onwards SDG of the other control systems were drawn considering the system is at steady state.

Chapter – 05

TWO ELEMENT CONTROL SYSTEM

5.1 INTRODUCTION:

Here the main objective of the two element control system is to control two variables. It is different from the cascade control system in which control of one variable keeps the other variable at desired value. In two element control system we need to adjust the two variables which are under focus and in this study we have considered a process in which the process variables to be controlled are flow rate and level control. Figure 13 shows a picture of two element control system which is under consideration.

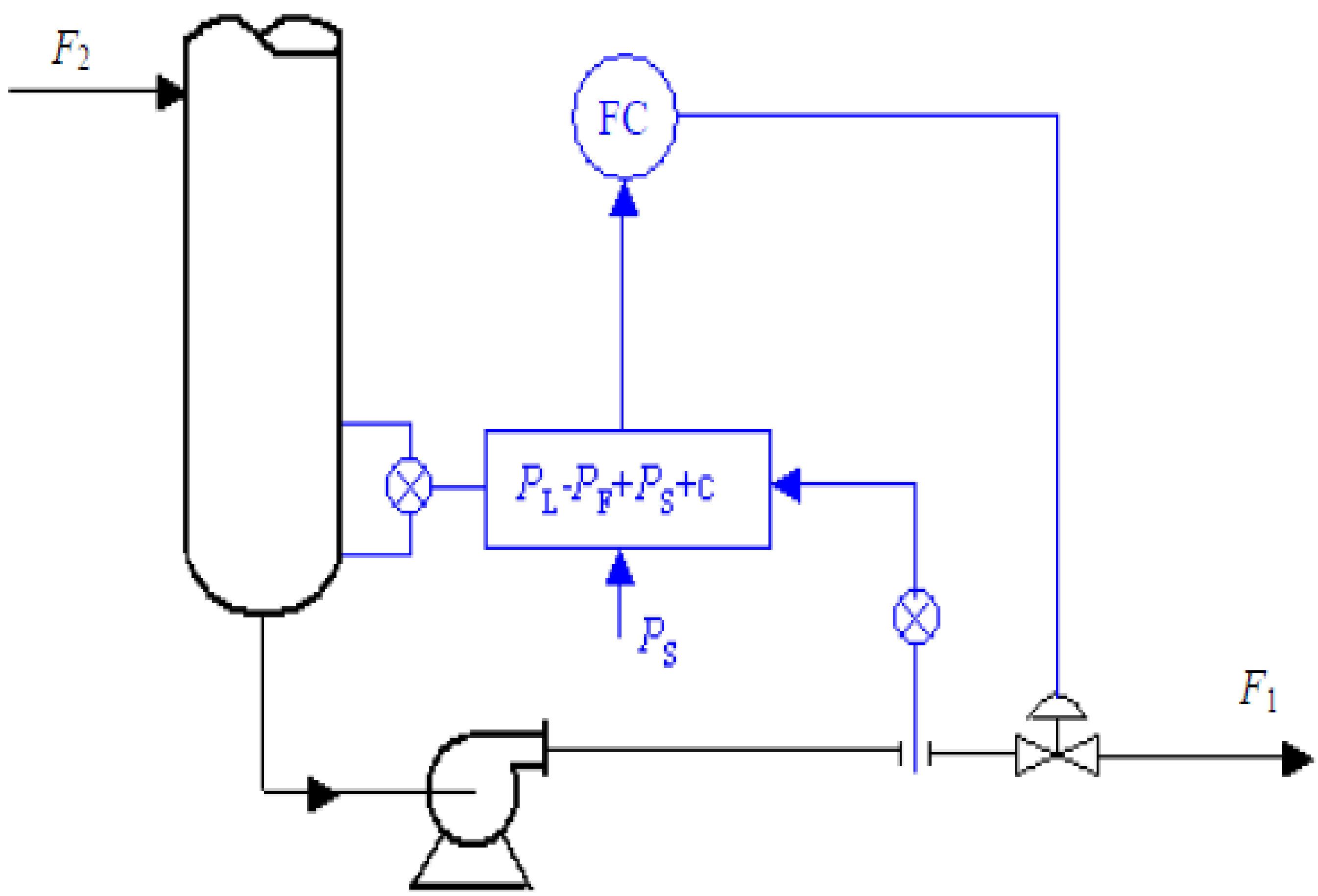

Figure 13: Two element control system

5.1.1 SYSTEM DESCRIPTION:

The main objective of the system that we have considered is to simultaneously maintain both the level and flow rate corresponding to the tank. Here to reduce the difficulty of understanding the system, the two process variables are converted in terms of Pressure signal. $P_x = P_L - P_F + P_S + c$ where P_x is the pressure signal of the adder, P_L, P_F are the pressure measurement signals of level and flow rate respectively and P_S is the tunable signal of the adder, and c is the constant. The block diagram of the two element control system is shown in Figure 14.

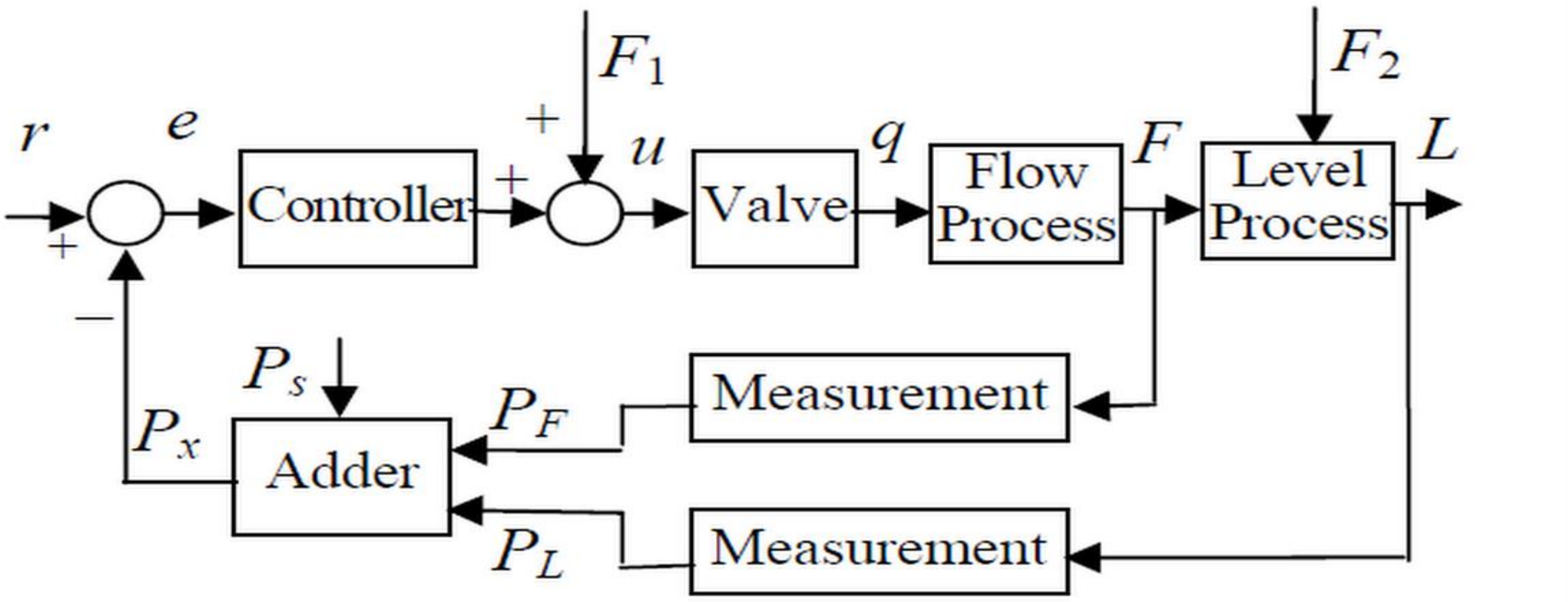

Figure 14: Block diagram of the Two element control system

Here in order to form the SDG, as per the algorithm we need to formulate the equations. From the block diagram it is easy to form the equations. F2 is to control the level of water inside the tank and F1 is to control the the flow rate. As already explained it is important to study the steady state SDG we have assumed that the system is at steady state and accordingly the value of error is zero, which leads to cancellation of two other nodes u_D and u_I. Initially both the level and flow rate are measured and they will get converted into pressure signals P_L and P_F respectively. Later both the signals are added using adder which is shown in the figure and its value is registered as P_X. Then it is measured against the set point “r” and then error is noted which enters into the controller as input and gives u as output signal. F_1 is added to the output signal which is inputted to the actuator and results in output signal q, which then goes through the process element gives F and then to Level process gives L which are measured and this process continues untill no error is registered in both level and flow rates. The equations corresponding to the steady state system are: **$e = r - P_X$ (22)**

$u + F_1 = k.q$ (23)

SDG of the two element control system is shown clearly in the Fig 16. In the figure it is clear that the level and flow have both positive and negative effects which is different from that of the cascade control system. Also in this case F_1 is registered as a deviation node and an incease in F_1 will register a decrease in the value of u_I .

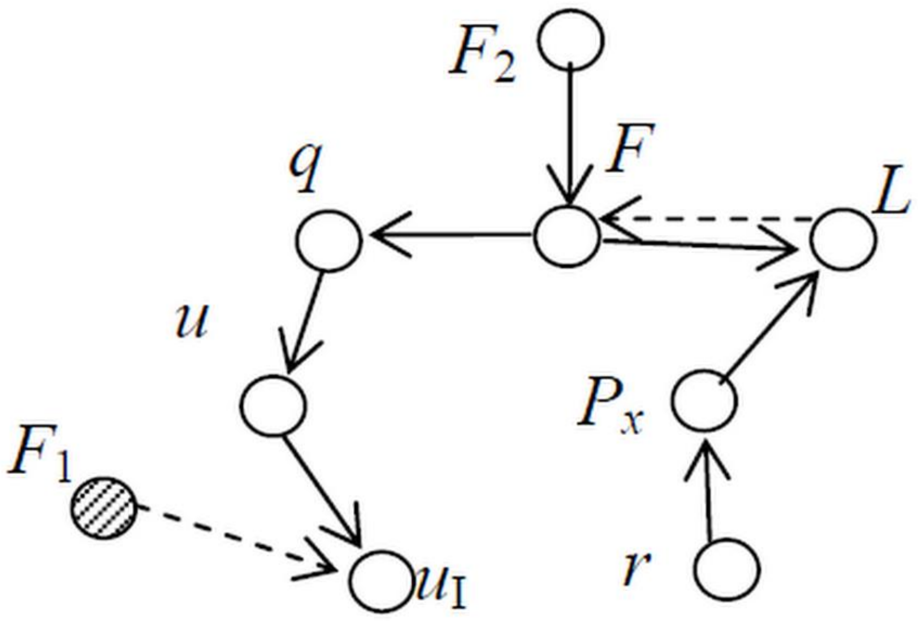

Figure 15: SDG of steady state Two element control system

5.1.2 FAULT PROPAGATION PATH:

From the above Steady state SDG it is easy to find the fault propagation paths. It is clear that there are two fault propagation paths and they are

(i) $r \rightarrow P_X \rightarrow L \rightarrow F \rightarrow q$

(ii) $F_2 \rightarrow F \rightarrow L$ & $F_2 \rightarrow F \rightarrow q \rightarrow u \rightarrow u_I$

Thus SDG of the two element control system and the fault propagations paths were determined. Based on this result it is easy to find the SDG's and fault propagation paths of various complex control systems. They can be obtained by the combination of several single control loops or sometimes the combination and connection of single and cascade control loops.

Chapter – 06

THREE ELEMENT CONTROL SYSTEM

6.1 INTRODUCTION:

One of the major application of three element control system is boiler drum. The main objective of the boiler drum is to maintain the level of water inside the drum by adjusting the steam flow and water flow. The performance of the three element control systemduring transient conditions makes it very useful for general industrial and utility boiler applications. Three element control system is a combination of cascade and feed forward control system.

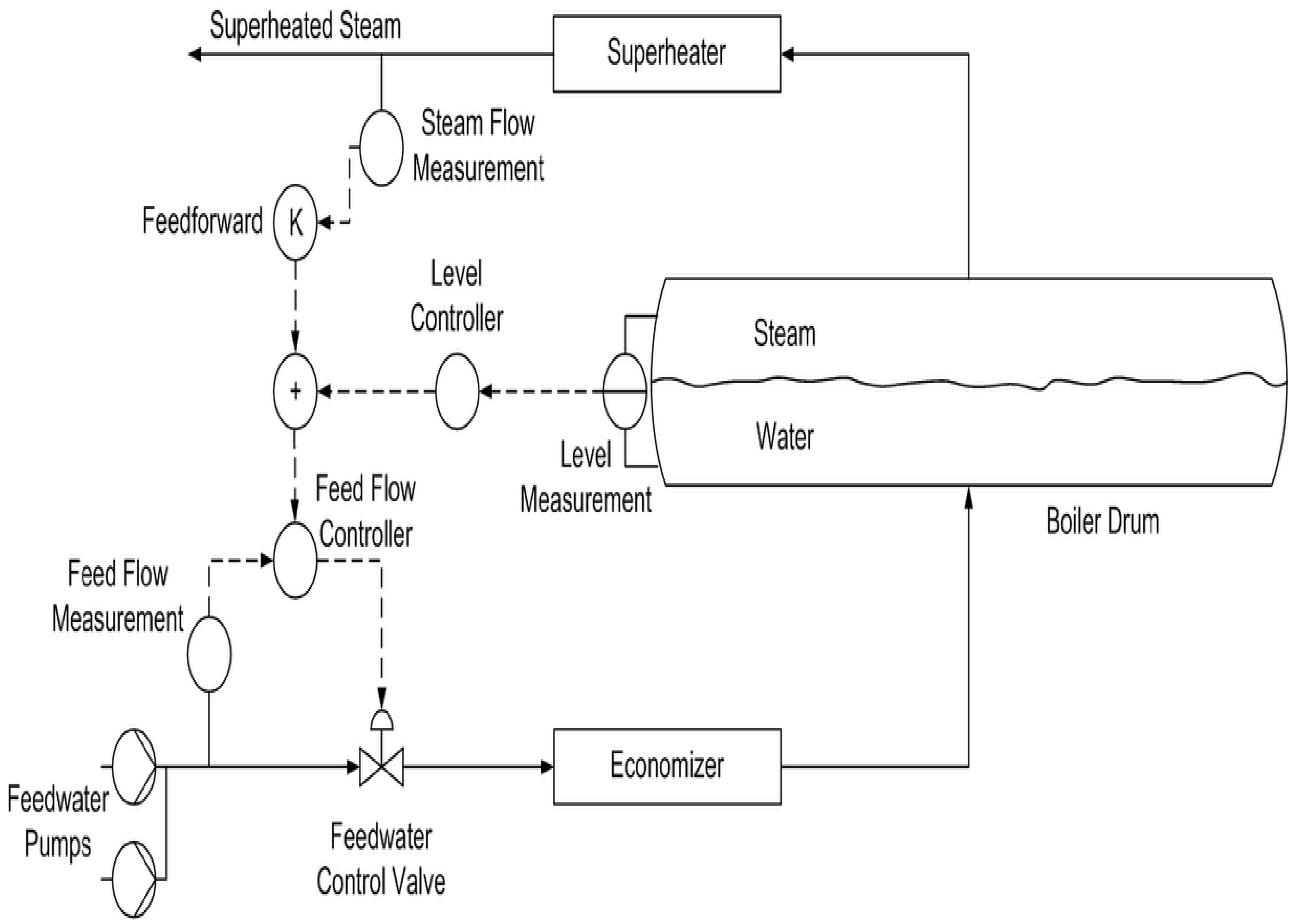

Figure 16: Three element control system- Boiler drum

6.1.1 SYSTEM DESCRIPTION:

For the feed water control system,the flow rate of steam is measured and it is used as the set point of the feed water flow controller. In this way the feed water flow is adjusted to match with the flow rate of steam. Any change which registers a deviation in steam flow rate will immediately adjusted because of the adjustments that tooks place with the flow rate of the feed water controller. In order to develop SDG for the three element control system it is necessary to develop a block diagram for the boiler drum.

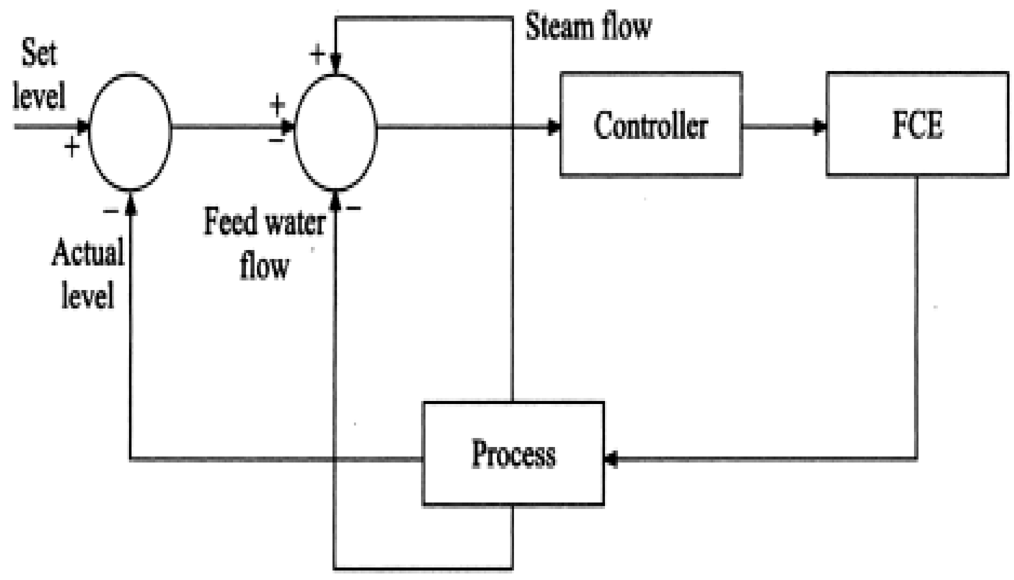

Figure 17: Schematic diagram of three element control system

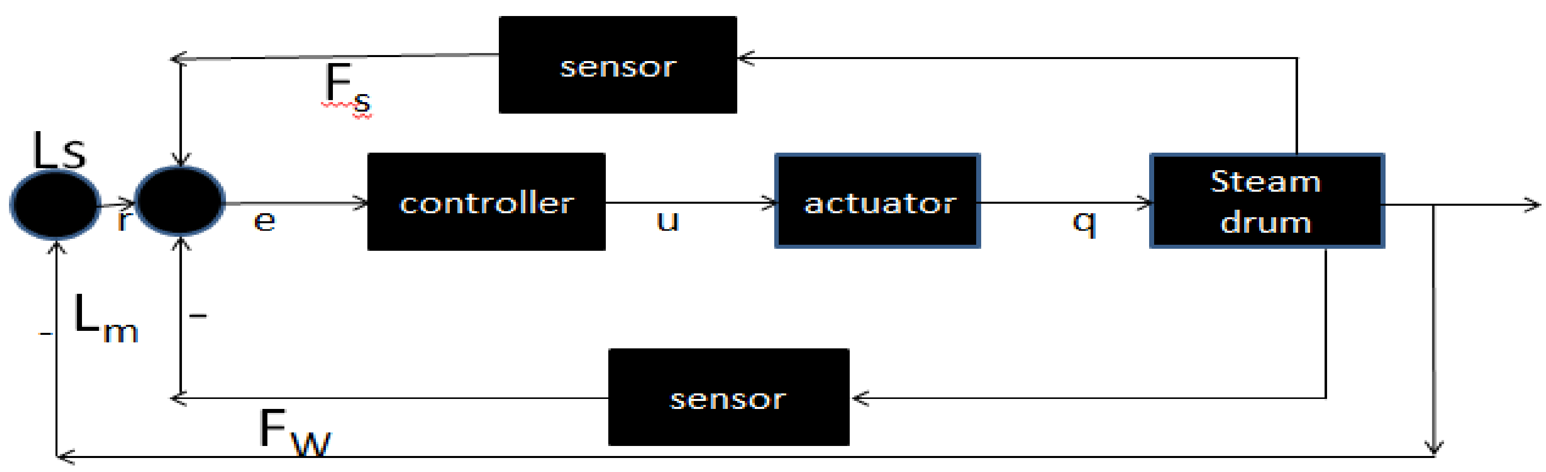

Figure 18: Block diagram of three element control system

Following the same conditions we can form the equations which are required to form the steady state SDG.

The equations involved in this three element control system are

(i) **Ls-Lm = r** **(24)**

(ii) **e = k.u** **(25)**

(iii) **u = k_v.q** **(26)**

Here k and kv are the the positive gains of the control elements respectively. The SDG of the three element control system is shown in Figure 19.

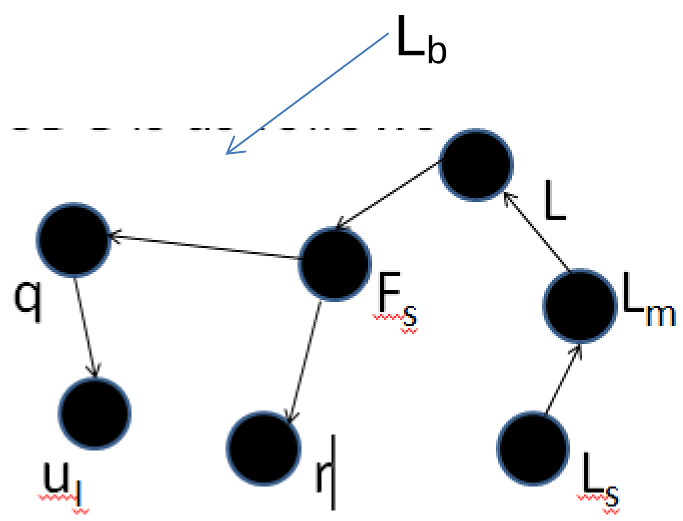

Figure 19: SDG of steady state three element control system

6.1.2 FAULT PROPAGATION PATH:

From the SDG it is clear that there are two fault propagation paths. They are

(i) Ls→Lm→L→Fs→r

(ii)L_b→ L→Fs→q→u_I

Thus the SDG and the fault propagation paths for the three element control system were also found out. In the SDG qualitative details of the three element control system we have considered only single loops to reduce the diffculty by neglecting some minor ones.

Chapter – 07

FUZZY LOGIC

7.1 FUZZY SIGNED DIRECTED GRAPH:

7.1.1 DEFINITION:

The concept of fuzzy graph is a natural generalisation of the crisp graphs using fuzzy sets. A crisp graph is denoted by the pair **G = (X,E)** where **X** is a finite set of nodes and **E** a non fuzzy relation on **X** x **X**. A fuzzy graph is a pair (**X'**, **E'**), where **X'** is a fuzzy set on **X** and **E'** is a fuzzy relation on **X** x **X**' such that $\mu_E \leq \min(\mu_{X'}(x), \mu_{X'}(x'))$. Here μ_E is the membership function of the binary effect of two adjacent nodes **x** and **x'** over a branch $\mu_{X'}$, the mebership function of the node. However, in some situations it may be desirable to relax this ineqality. If $\mu_{E'}$ and $\mu_{X'}$ only take the values of -1,0 or 1, then a fuzzy graph becomes crisp.

7.2 NODES:

Each node in a fuzzy-SDG is represented by a fuzzy variable. An example of value space of a node is considered. The number of fuzzy values covered by the fuzzy value space is determined by the problem requirements. It is worth noting that the method is not restricted to a three range pattern of -,+,0. Every legal value of node variable such as high and medium high is a fuzzy set **M'**. **M'** is therefore represented by its membership function, μ, such that the value of **μ** illustrates the degree of membership of the element x belonging to **M'**. whether a value of **x** belongs to **M'** depends on both the value of **μ** and the ƛ cut value of **M'**. the membership function, may take various shapes but the most common is the triangular and trapezoidal representations. In fuzzy signed directed graphs, node is uniquely defined by the following expression

Node_name (val, μ,υ, type, arrow-to-node-list,arrow-from-node-list)

In the above expression val represents the value of node such as high or low; ʋ is the smoothed valuein [-1,-1], of the real value of the variable such as 0.60 corresponding to 1.6 m for liquid level, μ is the membership function value, arrow to node list is the list of all node names to which this node points to and arrow from nodes list includes all node names from which the current node is being pointed to; type is the type of variable. A process variable can be one of the three types of variables: they are controlled level such as the liquid level shown in Fig 1. Measured variables such as flowrate and unmeasured variable such as valve opening. All controlled variables are measured variables.

7.3 WORKING WITH FUZZY LOGIC TOOL BOX:

The fuzzy logic tool box provides different types of GUIs to let us perform various classical fuzzy system development and pattern recognition. Using the fuzzy tool box, we can

(i) Develop and analyze fuzzy inference systems

(ii) Develop adaptive neuofuzzy inference systems.

(iii) Perform fuzzy clustering.

In addition, the toolbox provides a fuzzy controller block that we can use in Simulink to model and simulate a fuzzy logic control system.

7.4 BUILDING A FUZZY INFERENCE SYSTEM(FIS):

Fuzzy inference is a method that interprets the values in the input vector and based on user defined rules, it will assign values to the output vector. Using the GUI editors and viewers in the Fuzzy Logic Toolbox, we can build the rules set, define the membership functions and analze the behavior of FIS. The following editors and viewers are provided.

(i) **FIS editor**: It displays the general information about the Fuzzy inference system

(ii) **Membership function editor**: Lets you display and edit the membership functions associated with the input and output variables of FIS.

(iii) **Rule Editor**: It will help us in viewing and editing of Fuzzy rules using one of the three formats. Full English-like syntax, concise symbolic notation, or an indexed notation.

(iv) **Rule viewer**: It will give detailed behavior of FIS to help diagnose the behavior of specific rules or study the effect of changing input variables.

(v) **Surface viewer**: It generates a 3-D surface from two input variables and the output of an FIS.

In order to simulate fuzzy logic controller we need to develop an algorithm. The algorithm is as follows:

(i) For a given fuzzy logic controller or system we need to mention the number of inputs and number of outputs.

(ii) Each and every input and output is to be defined by some particular membership functions.

(iii) We need to develop the appropriate rules using experence and knowledge.

(iv) After defining rules, the only step remaining is to do simulation and to conduct the fault analysis.

To understand a simple system was initally studied.

7.5 CASE STUDY- CSTR:

Let us consider a simple example of jacketed CSTR in which a simple reaction A + B → C. Here in this system there are two inputs and one output. Before going to simulate this model, we need to predefine the objective of the problem. Basing on the amount of both A and B reacted we will have the output product C. We will define the range of the output product C on the basis of 10 point scale. Before going to do the simulation we need to define the cases. Here we have consider three cases.

They are:

(i) If the amount of reactants A & B is less, then the amount of product formed is less.

(ii) If the amount of reactant A is average, irrespective of B,then the amount of product formed is medium.

(iii) If both the amounts of reactants reacted are large,then the amount of product formed C is also large. In terms of fuzzy logic it is excellent.

After defining the three cases, we can go for simulation. As per the algorithm we have already mentioned the number of inputs and number of outputs in the system. In this case there are two inputs and two outputs in our system. In the command space of the Matlab type **fuzzy .** After entering this command , Matlab will open a FIS editor which is shown in Fig 21. In default window it seems that there are one input one system and another output. we need to add one more input through the edit tab placed in the FIS editor.Then after adding input the FIS editor,it will change as shown in Figure 21. Finally we have two inputs and one output and next thing to do is defining the inputs and then the membership functions. We can directly define the inuts by highlighting the input and output variables. We can give a name to our variables. Let us say our input and output variables are A, B, C respectively.

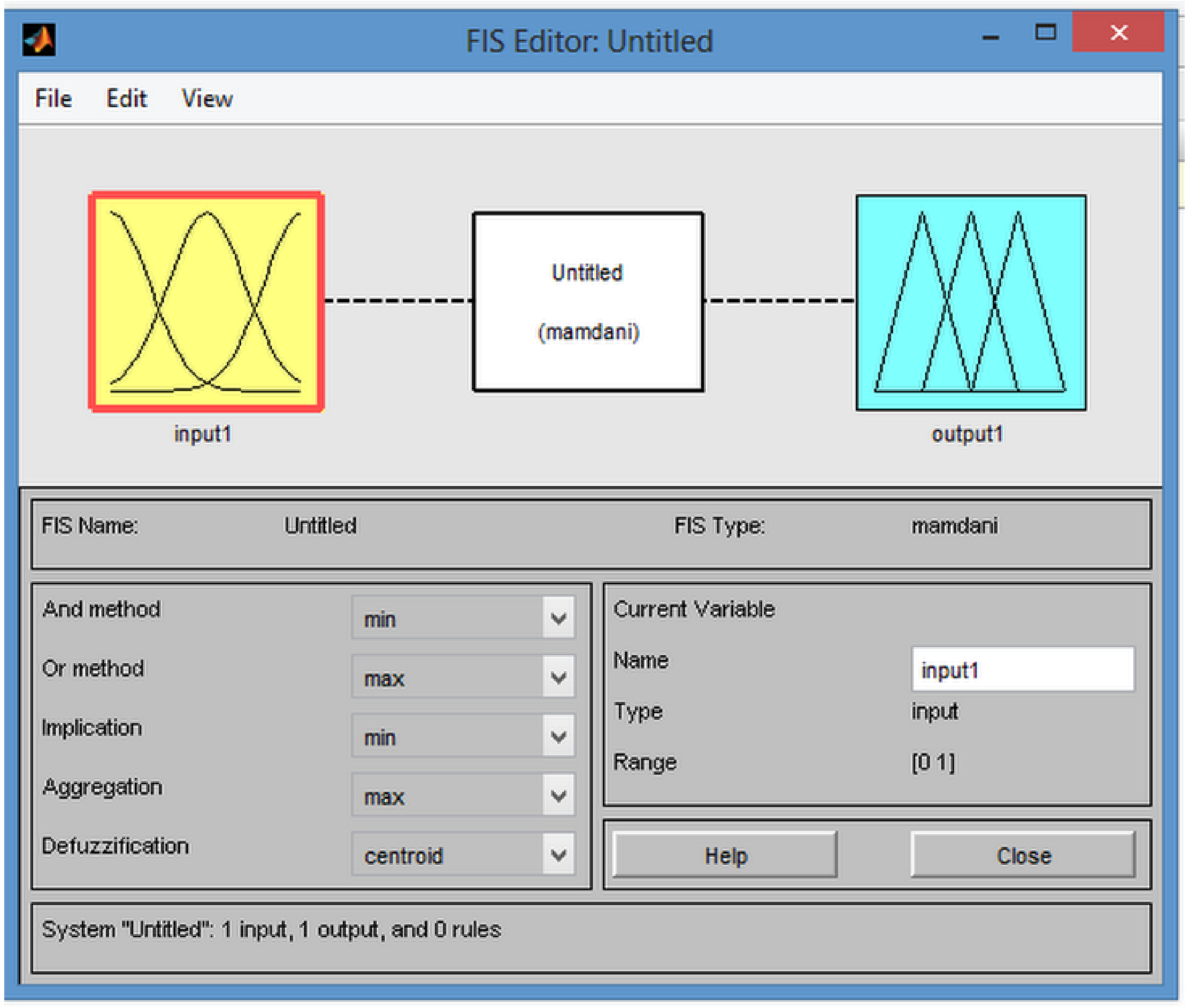

Figure 20: FIS Editor

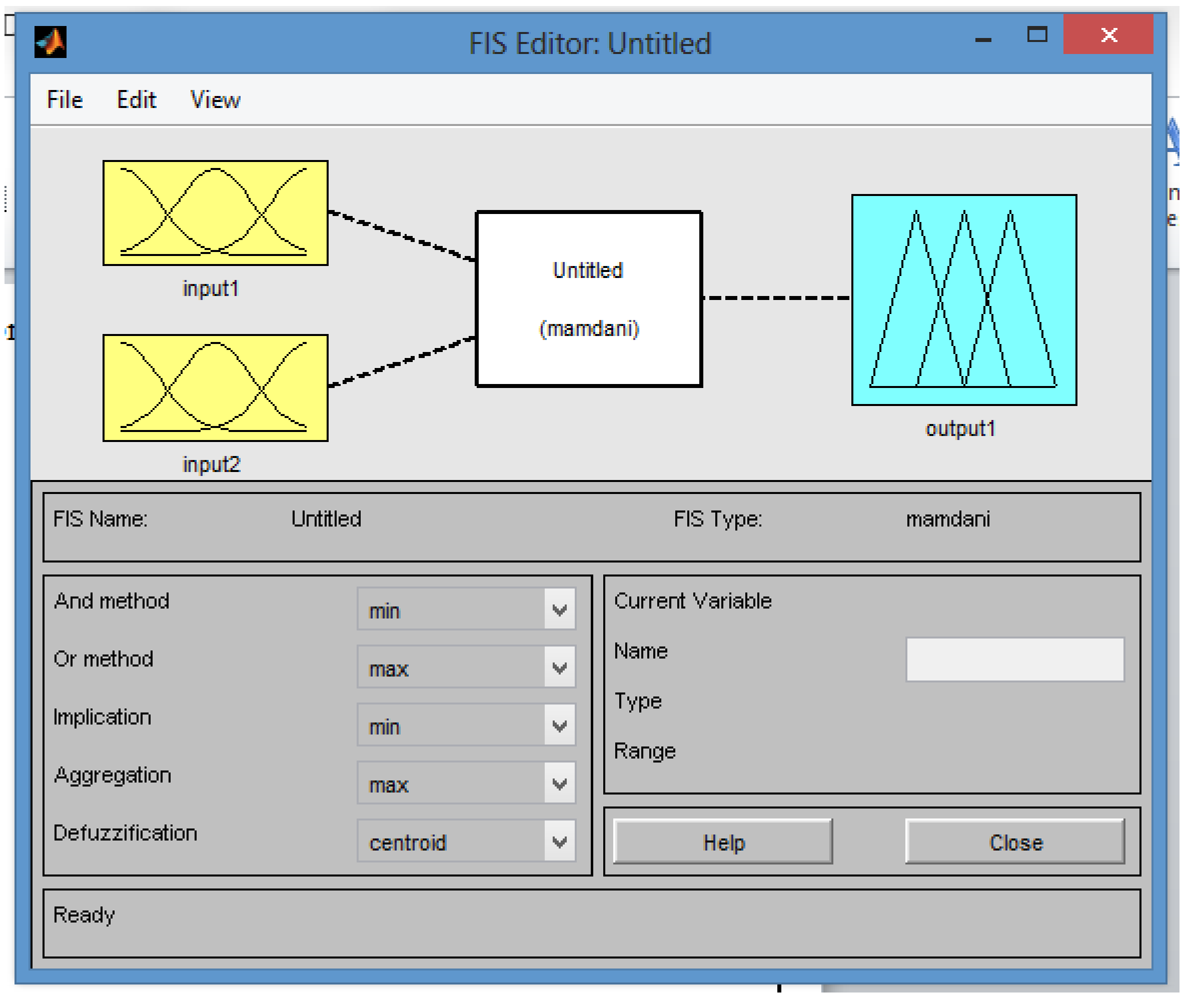

Figure 21: Modified FIS editor with two inputs

After defining the input and output variables as A, B and C then we need to define the membership functions. This is done in Membership function editor which is shown in Figure 22.

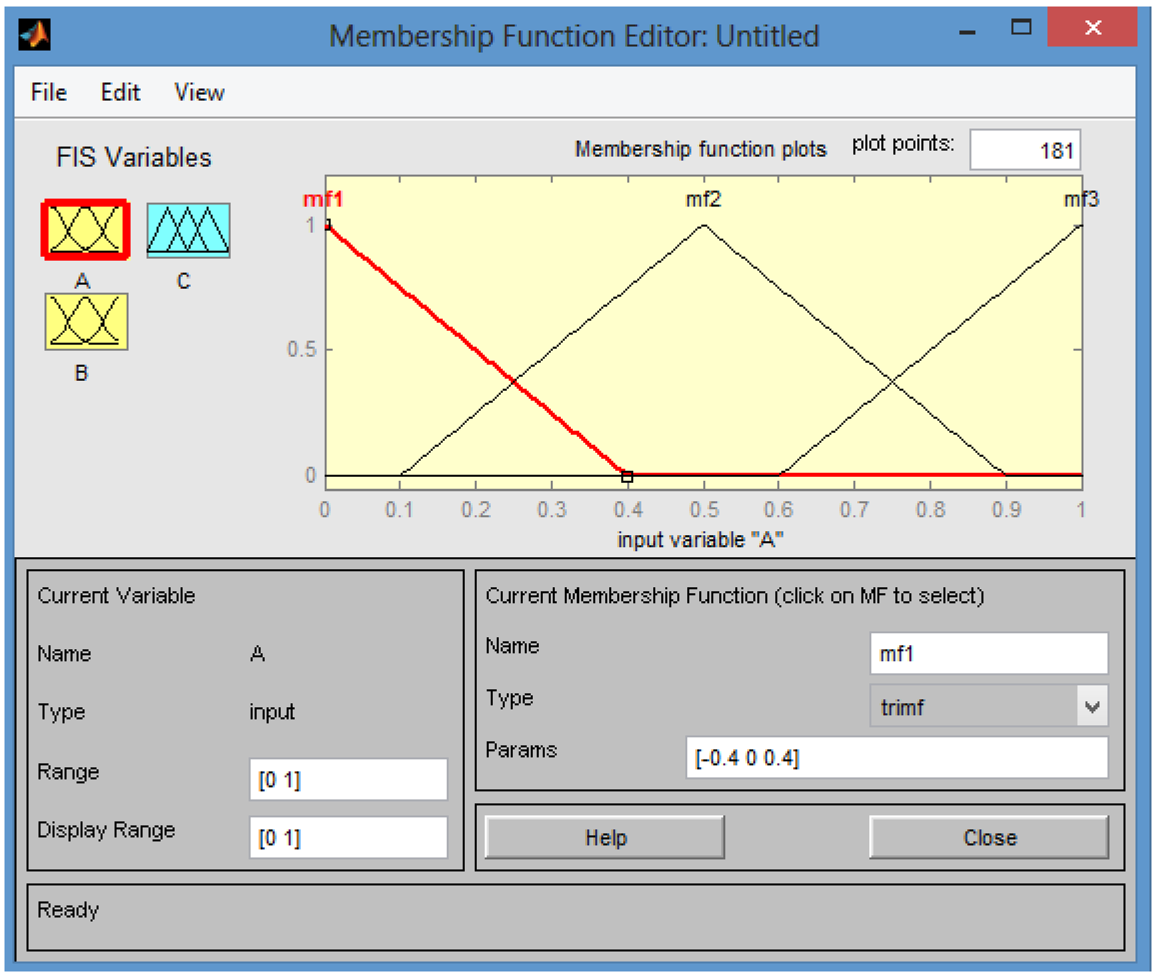

Figure 22: Membership Function editor.

Here in this editor we can edit and add the membership functions as per our wish. For input varible A we are considering the membership function gaussmf and for the other input varible we are considering the membership function as trapmf and for this variable we are defining only two membership functions they are less amount and large amount considering in case two only A is reacting giving product B in an average amount. After this, then for the product C we need to again develop membership functions. For the product C we have considered trimf as the membership function from the membership function editor. Then after this we need to develop the rules to the logic box. These rules are generated using the rule viewer from the FIS editor and the rule box is shown in Figure 23. Rules are nothing but the cases that we have defined previously.

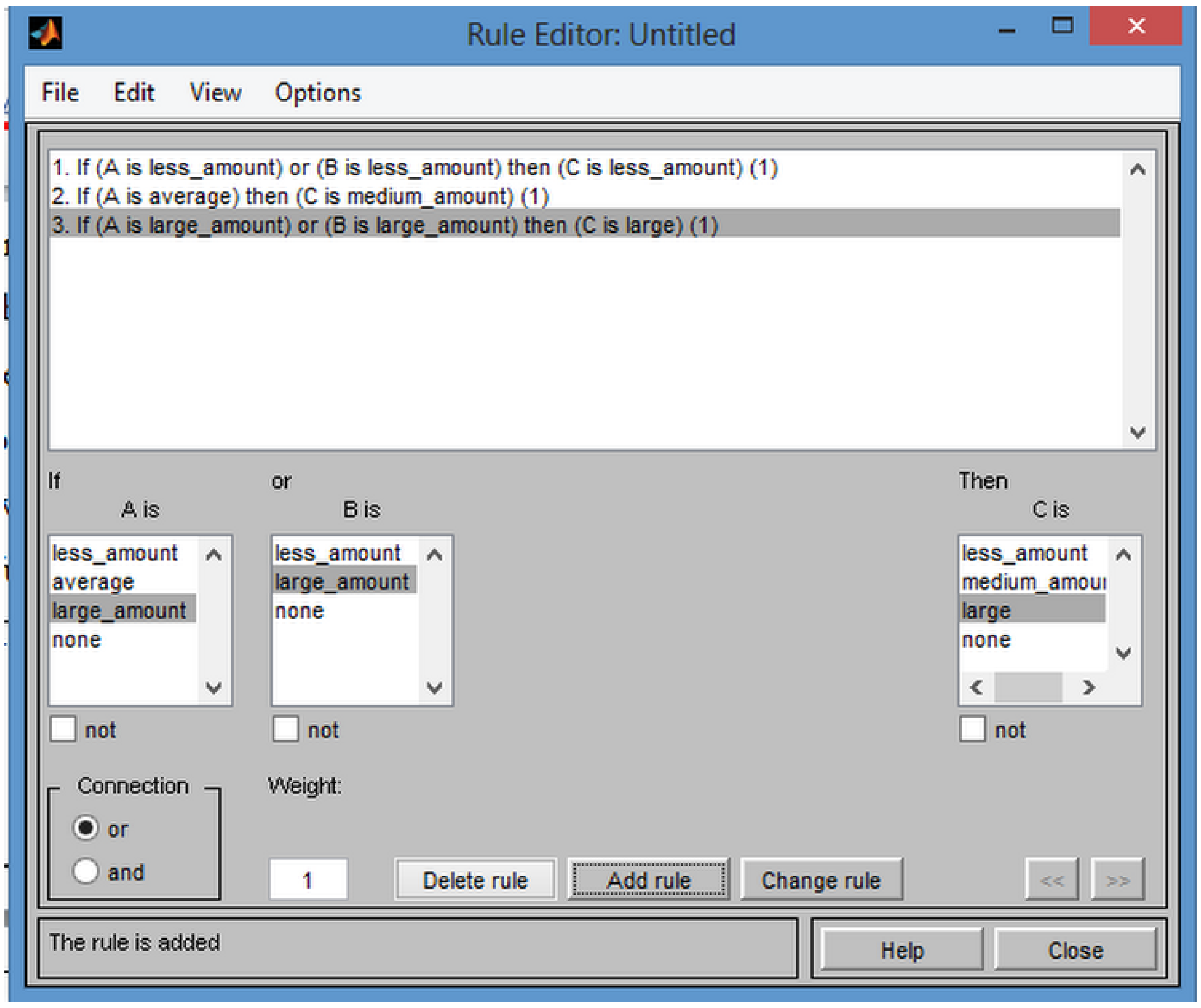

Figure 23: Rule Editor

Following our previous algorithm, after defining the rules we can go for fault analysis. It can be done through two viewers. One is rule viewer as shown in Figure 24 and the other one is Surface viewer shown in Figure 25.

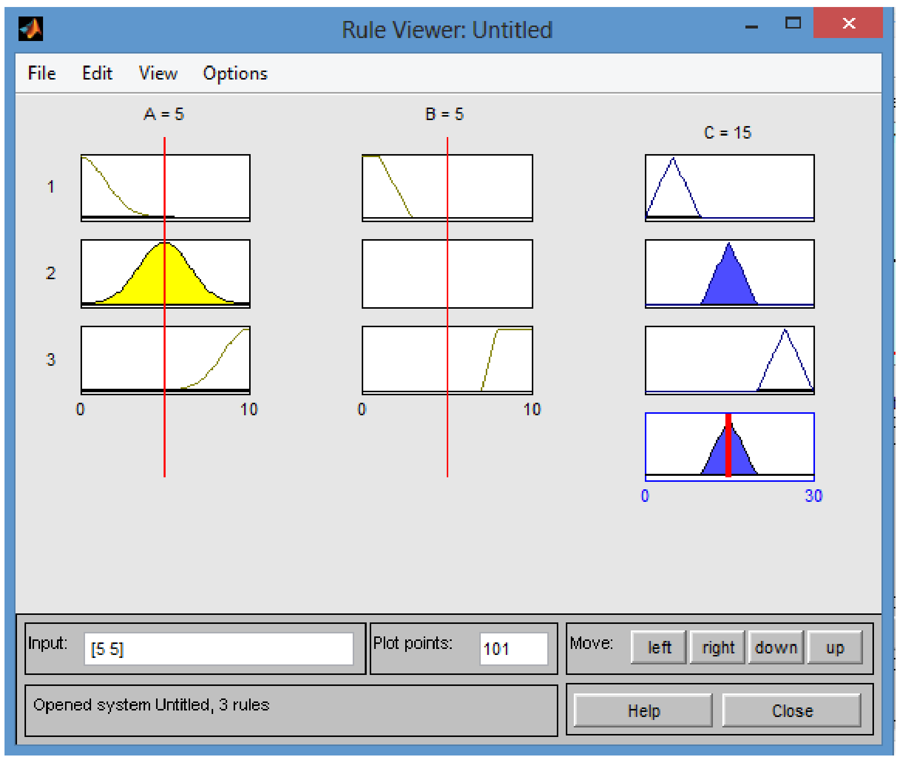

Figure 24: Rule viewer

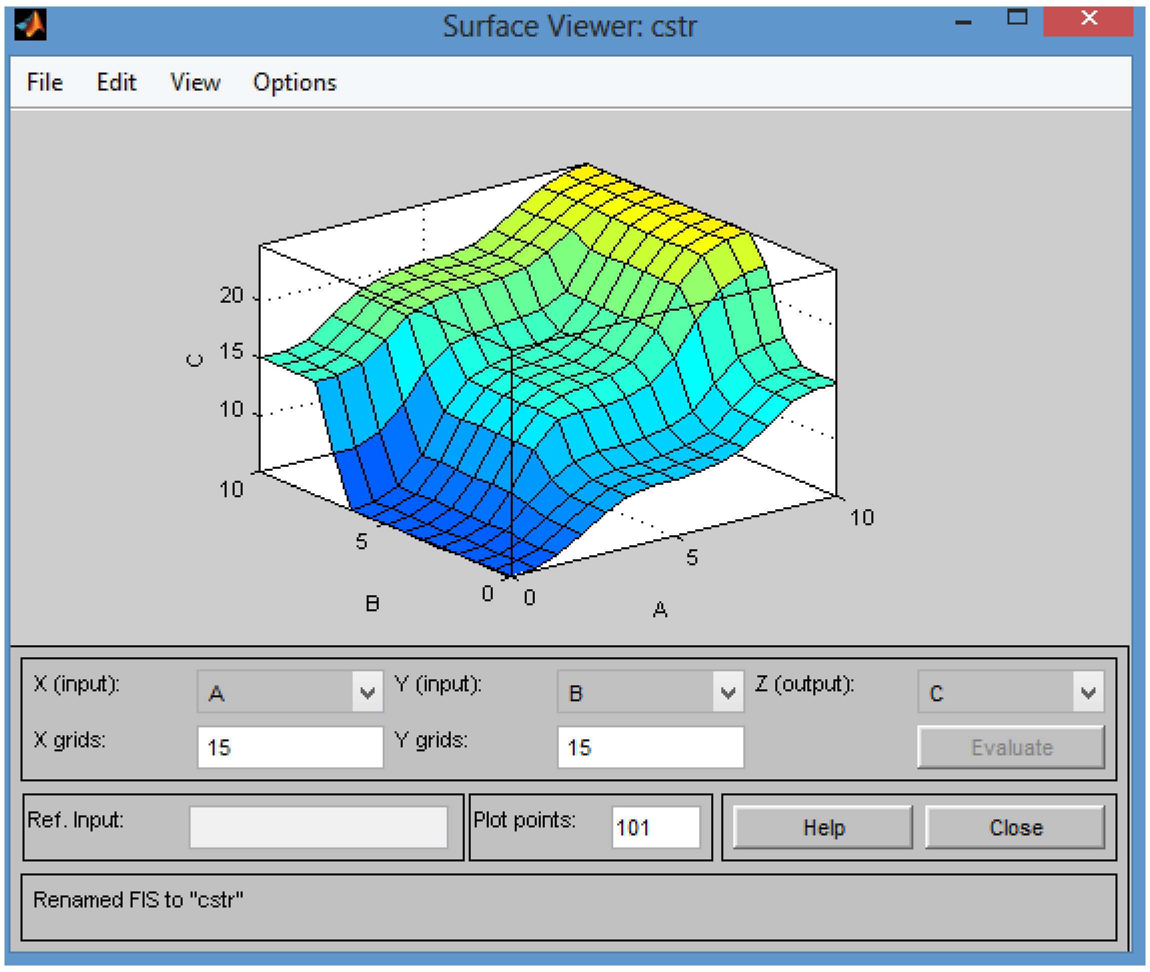

Figure 25: Surface viewer.

By changing the values in rule viewer we can easily find how the output is getting affected by the input variables. Even in complex scale industries once if we define the number of inputs and number of outputs it will be easy for us to say how the output gets effected by a particular variable. It gives us a good logical reasoning in fault diagnosis. Using Fuzzy SDG will definitely reduce the time required to do fault diagnosis and also we can easily validate the results in case of Fuzzy SDG.

Table 4: Effect of input variables on the output variables

Amount of A	Amount of B	Amount of C
5	5	15
2	2	8
7	7	16
8.5	9	25
9.5	10	26

Chapter – 08

CONCLUSIONS

&

RECOMMENDATION

8.1 CONCLUSION AND RECOMMENDATION:

The advantages of Signed Directed graph are

(i) The SDG method discusses in detail the various possible faults that might happen in the system and the fault propagation paths through which fault is propagated, thus giving a proper analysis of the system.

(ii) Fault can be traced back to its root cause using Inverse inference mechanism or by using the Bidirectional inference.

(iii) SDG, once fully developed and validated using some theories or simulation programs, then it is so easy to study and even ordinary workers in process industries can understand without any special education. They can easily carry out the fault detection and analysis by having proper SDG of the process system.

The main Disadvantages of Signed Directed Graph are:

(i) SDG gives qualitative analysis. The deviations in the process variables are assigned the states of high, low or steady state. The actual quantity of increase or decrease in the process variable is difficult to measure.

(ii) All the SDGs developed are based on the theoretical knowledge and logical reasoning; there is a chance that the SDG may susceptible to errors and hence it needs huge checking before it is going for implementation in process industries.

In order to overcome these problems Fuzzy Signed Directed graphs were studied and the main advantages of Fuzzy SDG's are they combine Fuzzy logic with the signed Directed graphs and the combination gives good resolution of fault diagnosis in process industries. More improvements can be brought up in Fuzzy logic reasoning which can give more efficient way for fault diagnosis. It gives good qualitative reasoning of fault diagnosis. And the results can be easily validated. The fuzzy-SDG consists of nodes which are described by fuzzy quantity spaces such as high, medium high, low, medium low and normal steady state value. The advantages of this approach are it generates fewer ambiguous solutions, which can give a more precise description of the variables than the -, 0, +of the normal SDG and it also produces a casual explanation. Fuzzy logic can also be used for various reasoning tasks such as complex multiple fault diagnosis of process industries, operational supervision and simulation of operations.

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