FAULT TOLERANT CONTROL MECHANISM: APPLICATION TO PANCF COAGULATION BATH

[1]Eswararao Koppaka, [2]U.V. Ratna Kumari
[1]M.Tech Student, [2]Associate Professor
[1]Department of Electronics and Communication Engineering
[1]University College Of Engineering, JNTUK Kakinada, East Godavari, A.P, India

Abstract: Fault Tolerant Control mechanism for a Coagulation bath of polyacrylonitrile carbon fiber (PANCF) production line is presented in this paper. Active fault tolerant control methods focused on designing a Controller on the Reconfiguration approach to maintain the desired closed loop system performance under partial (actuator) faults. The control mechanism in this paper designed based on fault hiding reconfiguration approach. The designed controller placed in fiber production line, and simulation experiments conducted. The conducted simulation experimental results demonstrate that, the designed Controller performing satisfactorily for single and multiple actuator faults.

Index Terms: **Fault Tolerant Control System (FTCS), Coagulation bath, Polyacrylonitrile carbon fiber (PANCF), Reconfigurable-Controller (RC), Fault-hiding reconfiguration approach.**

I. INTRODUCTION

It is very common, in case of large and complex systems, faults or malfunctioning of the system components takes place due to internal or external disturbances. The fault or malfunctioning of the components of the system may leads to undesired behavior of the system. So, the satisfactory performance of all the components is a basic necessity to get the desired performance of the system. In complex system with multiple input and multiple output, the disturbance or fault in one component may leads to the system failure due to the coupling between the components / loops. To avoid the process hampering due to faults in a plant, it is necessary to limit the fault to its particular component/ loop i.e. decoupling need to be performed to uncouple the faulty one from healthy ones. Further a suitable control action need to be apply on faulty component / loop. Control equipment will take care of all these things, such that, the system gives the desired performance under component malfunctions, such systems are called as Fault Tolerant Control Systems (FTCS)[2].

FTCS classified [2] as, passive fault tolerant control systems (PFTCS) and active fault tolerant control systems (AFTCS). In PFTC, controller designed with the objective of the system to become insensitive to some priori known faults [3]. Alternately, AFTC design a new control scheme (Re-configurable / Re-structurable) to overcome the consequences takes place in a plant due to the faults / component mal-functions. The different control design approaches / mathematical tools [2] are Linear quadratic, Pseudo-inverse (model matching is an improved method of Pseudo-inverse method), Intelligent control, Gain scheduling, Integrated diagnostics and control, Eigen structure assignment, Feedback linearization, H_∞ robust control, and Linear matrix inequality.

Different Reconfiguration approaches [2] are Fault hiding, optimization control schemes, Probabilistic approaches and learning control. System parameter estimation and system identification in online are two main things help to design a reconfigurable controller to improve the active fault tolerant control system performance [2,5]. Probabilistic approach for component malfunctions is presented in [4]. In case of fault hiding [6, 7], it is to be ensured that the output of the plant under faulty condition is same as that of the fault free condition. To achieve this, a reconfigurable compensator is designed to hide the faulty behavior.

Fault may take place in Actuator or in Plant or in Sensors. Fault hiding approach for partial Actuator faults is used in this paper. The paper is presented as follows. Section-II deal with Fault Tolerant Control System for Actuator faults. The concept of Control theory is described in section-III. The designed controller applied on the PANCF Coagulation bath, Simulation Experiments and Results furnished in Section-IV. Finally the paper concluded in Section –V.

II. FAULT TOLERANT CONTROL SYSTEM FOR ACTUATOR FAULTS

The Fig.1 represents a Control system that consists of the Decoupling controller, Actuator, Plant, Actuator Fault diagnosis unit and Reconfiguration mechanism.

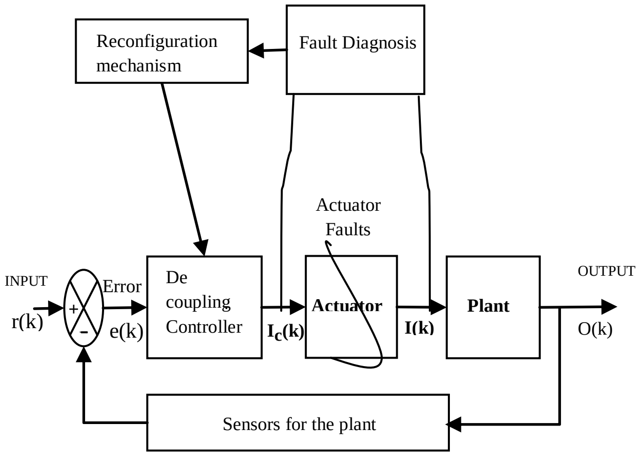

Fig 1. Fault Tolerant Control system for Actuator faults

Where, r(k) is the set point of the system , O(k) is the controlled output of the plant , e(k) is the control error input to the Decoupling controller, $I_c(k)$ is the actuator's controlled input, I(k) is the actuator's output (or the input to the plant).

2.1 Actuator:

The normal mapping model of the actuator is:

$$I(k) = f(I_c(k)) \qquad (1)$$

Where, $f(I_c(k))$ is the equivalent theoretical output of the Actuator actual output of I(k). Equation (1) holds good, under normal operating conditions of the actuator only.

The common type of actuator faults are freezing, saturation (is also one type of freezing fault), offset bias and damage coefficient type. The general fault model of the actuator 'a' [8].is given in equation (2),

$$I(k) = d_a \cdot f(I_c(k)) + o_a \qquad (2)$$

Where d_a is the damage coefficient and o_a is the offset bias.

The transfer function of the faulty actuator is (considering only damage coefficient and offset bias):

$$G_{P_a}(s) = d_a + \frac{o_a}{s} \qquad (3)$$

Where, $d_a \in [0,1]$ and $o_a \in [0, I_{amax}]$.

If $d_a = 0$, then $G_{P_a}(s) = \frac{o_a}{s}$, actuator stuck fault. If $d_a = 0$ and $o_a = I_{a\,max}$, then $G_{P_a}(s) = \frac{I_{a\max}}{s}$, it means that, the actuator is saturated. If $o_a = 0$, then $G_{P_a}(s) = d_a$, it means that, the actuator is damaged with coefficient of d_a. If $d_a = 1$, then $G_{P_a}(s) = 1 + \frac{o_a}{s}$ and if $d_a = 1$ then and $o_a = 0$, the actuator is normal.

2.2 Plant (PANCF coagulation bath):

The quality of fiber out from the roller in the final stretch process of fiber production line is mainly depends on three parameters of the coagulation bath, those are the temperature(T), concentration(D), and liquid level(H) in the bath of coagulation process. Stabilization of these parameters is the main target of control system. The coagulation solution constitutes of high concentration DMSO (dimenthylsulfoxide), Hot water and Cold water. To maintain the Liquid level, Temperature and Concentration in the bath are at their set values, the bath should discharge the sparse solution at an appropriate rate. The arrangement of Coagulation process is shown in [10] Fig.2.

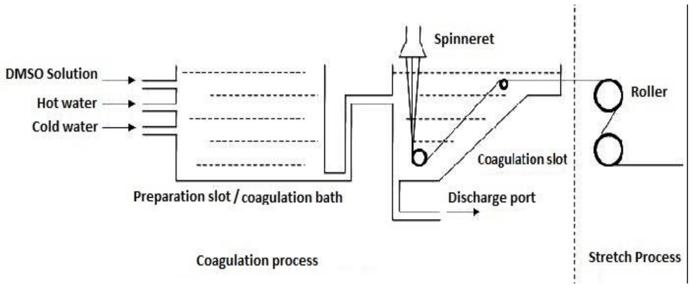

Fig 2. Coagulation Process in Fiber production plant

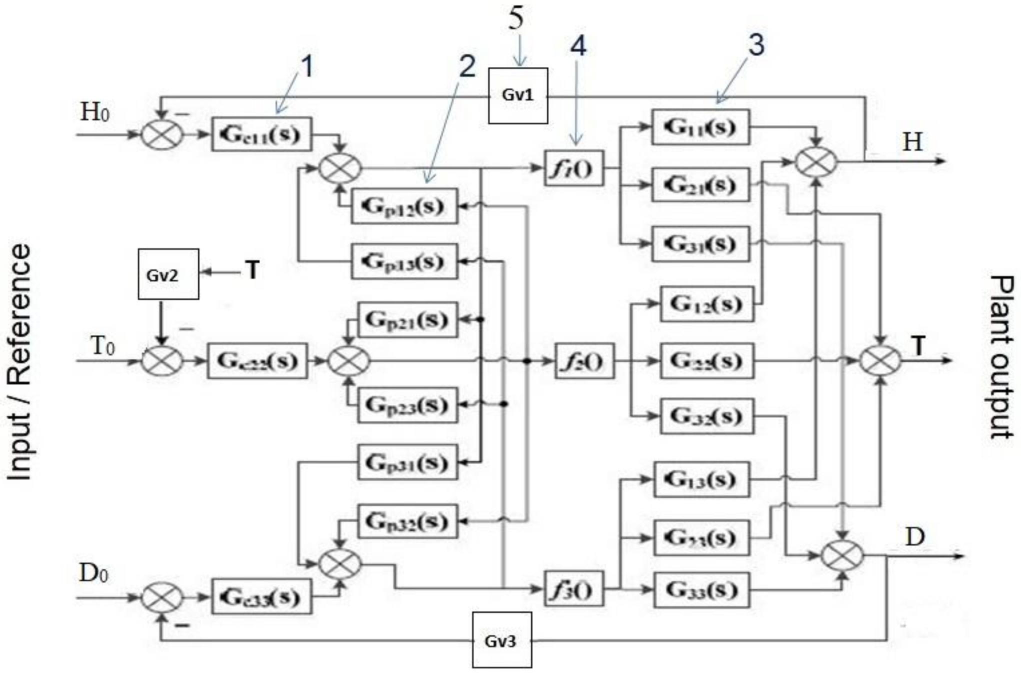

Fig 3. Detailed Structure of the controlled fiber process plant[9]

Where, H_0, T_0 and D_0 are the set values of level loop, temperature loop and concentration loop respectively. Liquid-level loop numbered as loop1 and actuator in this loop is named as 'a', DMSO solution flow through this actuator. Temperature loop numbered as loop2 and actuator in this loop is named as 'b', hot water flow through this actuator. Concentration loop numbered as loop3 and actuator in this loop is named as 'c', cool water flow through this actuator.

1. $G_{c\,mm}$: Loop controllers / PID controllers.
2. $G_{p\,mn}$: Decoupling compensators / Reconfigure blocks.
3. G_{mn} : Plant parameters .
4. $f_m(.)$: Actuator function model
5. G_{vm} : Feedback sensors.

Where, m = n = 1, 2, 3 indicates the loop numbers.

The mathematical modeling of the coagulation bath [10] is shown below:

$$\begin{bmatrix} H(s) \\ T(s) \\ D(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) & G_{13}(s) \\ G_{21}(s) & G_{22}(s) & G_{23}(s) \\ G_{31}(s) & G_{32}(s) & G_{33}(s) \end{bmatrix} \begin{bmatrix} I_1(s) \\ I_2(s) \\ I_3(s) \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} H(s) \\ T(s) \\ D(s) \end{bmatrix} = \frac{1}{As+\frac{1}{R}} \begin{bmatrix} e^{-\tau_1 s} & e^{-\tau_2 s} & e^{-\tau_3 s} \\ \frac{T_{DMSO}-T_0}{H_0} e^{-\tau_1 s} & \frac{T_{H_2O,H}-T_0}{H_0} e^{-\tau_2 s} & \frac{T_{H_2O,L}-T_0}{H_0} e^{-\tau_3 s} \\ \frac{D_{DMSO}-D_0}{H_0} e^{-\tau_1 s} & \frac{D_{H_2O,H}-D_0}{H_0} e^{-\tau_2 s} & \frac{D_{H_2O,L}-D_0}{H_0} e^{-\tau_3 s} \end{bmatrix} \begin{bmatrix} I_1(s) \\ I_2(s) \\ I_3(s) \end{bmatrix} \tag{5}$$

Where A: The slot bottom area, R is the hydraulic resistance of the port, τ: the lag coefficient (Mechanical systems need some delay respond to the changes in input signals).

2.3 Reconfigurable Controller:

It consists of loop controllers, Reconfigurable Compensators (loop controllers and decoupling compensator cumulatively called as Decoupling Controller) and Reconfigure block.

2.3.1Decoupling controller:

During initialization, the decoupling controller [11] behaves as Conventional Decoupling Controller (CDC). It uncouples the interactions between the loops to the maximum extent. The coupling effect is treated as external disturbance and accordingly the compensators designed. The details of the decoupling process are presented in [10]. The CDC includes, the loop controllers G_{cmn} (s) and decoupling compensators G_{pmn} (s), where m, n = 1, 2, 3, …. ($m \neq n$) for j number of loops in the control system.

The decoupling compensator transfer function [12] is given by

$$G_{p_{mn}}(s) = -\frac{G_{mn}(s)}{G_{mm}(s)} \qquad (6)$$

Where G_{mn} (s) and G_{mm} (s) are the plant parameters.

III. CONTROL THEORY

Control theory basically suggests two types of approaches, those are, Passive approach and active approach. Control Reconfiguration [6, 9] is an active approach, in this approach, the control loop is reconfigured according to the fault case to prevent failure at the system level. Control reconfiguration mechanism reconfigures the decoupling controller. The fault hiding reconfiguration approach is used in this paper.

3.1Fault hiding Reconfigurable approach [14]:

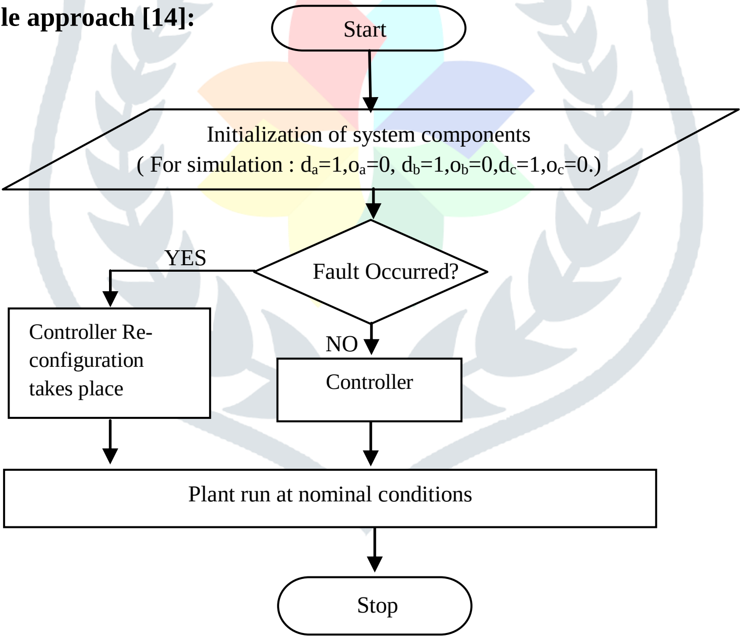

Fig.4. Overall Procedure of Plant control with Re configuration approach

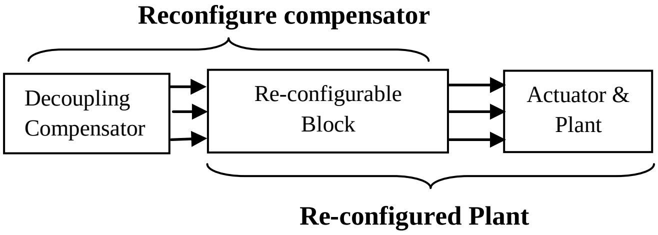

Fig .5. Block diagram of Fault hiding approach

A re-configurable block is placed between the faulty actuator/plant and nominal controller. Together with the faulty actuator/plant, it forms the reconfigured system. Even the actuator/plant in faulty condition, the reconfiguration block has to fulfill the requirement that the behavior of the reconfigured system should match with the behavior of the fault-free system.

The Reconfigure compensator block frequency model is as follows,

$$G_{p_{mn}}(s) = -\frac{G_{p_n}(s).G_{mn}(s)}{G_{p_m}(s).G_{mm}(s)} \qquad (7)$$

$$G_{p_{nm}}(s) = -\frac{G_{p_m}(s).G_{nm}(s)}{G_{p_n}(s).G_{nn}(s)} \qquad (8)$$

The designed compensators in equation 7 & 8 are used in place of decoupling compensator in Decoupling Controller to form Reconfigurable controller. Under plant normal operating conditions the damage coefficient equal to 1 and offset bias is equal to 0, so the transfer function fault model equal to 1. It means that under normal conditions, the Reconfigurable Controller behaves as a Conventional Decoupling Controller. Whenever fault occur in any actuator in the loops, accordingly the controller reconfigured and the plant get back into normal operating conditions within less time.

The parameters of the loop controllers [14, 15] are optimized by doing step test followed by using the PID tuner.

IV. SIMULATION EXPERIMENTS AND RESULTS:

The plant and controllers are initialized with the parameters [12] furnished in Table-I and II. The model developed using MATLAB R2017a software in a computer with core i5 processor and 4-GB RAM.

TABLE – I

NAME	VALUE	NAME	VALUE
A/m^2	0.15	T_{DMSO} / ℃	30
R	1	$T_{H_2O,H}$ / ℃	65
H_0	0.1	$T_{H_2O,L}$ / ℃	10
τ_1	1	T_0 / ℃	15
τ_2	1	D_{DMSO} / %	0.80
τ_3	1	$D_{H_2O,H}$ / %	0.001
--	--	$D_{H_2O,L}$ / %	0.001
--	--	D_0 / %	0.65

For the specified values mentioned in the Table-I, the plant in equation (5) can be written as follows:

$$\begin{bmatrix} H(s) \\ T(s) \\ D(s) \end{bmatrix} = \frac{e^{-s}}{0.15s+1} \begin{bmatrix} 1 & 1 & 1 \\ 150 & 500 & -50 \\ 1.5 & 6.49 & 6.49 \end{bmatrix} \begin{bmatrix} I_1(s) \\ I_2(s) \\ I_3(s) \end{bmatrix} \qquad (10)$$

TABLE - II
INITIAL PID PARAMETERS

Loop Name	Reconfigurable Controller
Loop-I	
P	0.35
I	0.8
D	0
Loop-II	
P	0.006
I	0.0015
D	0
Loop-III	
P	0.35
I	0.1
D	0

Table- III

LOOP	VALUE
Liquid- level	0.1 m
Temperature	15°C
Concentration	0.65

The Actuator functional equivalents [12] are considered as $f_1(.) = f_2(.) = f_3(.) = 1$. Here mainly concentrated on offset bias type faults in Actuators.

Experiment 1: **Offset bias fault of cold water valve $o_c = 0.15$ is simulated at t = 20s.**.

Actuator fault model is: $G_p(s) = d_c + \frac{o_c}{s}$

$$G_p(s) = 1 + \frac{0.15}{s} = \frac{s + 0.15}{s} \qquad (11)$$

The fault occurred in Actuator 'c' i.e. loop 3. So the de-coupler will uncouple the loops 1 and 2 from loop 3, and reconfigure the blocks corresponding to the decoupling compensators $G_{p_{12}}, G_{p_{21}}, G_{p_{23}}, G_{p_{32}}$ such that the plant parameters get back to its nominal values or set values . The result of the above fault case is shown in below figures 6 & 7. The performance of the reconfigurable controller is shown in Fig 6 & 7. The Plant with Immune Reconfigurable controller [12] for the above fault case is shown in fig. 8 , IRC is taking around 5 seconds of time to get back to its nominal value, where as the proposed reconfigurable controller is taking less than one second to get back to its set value after fault.

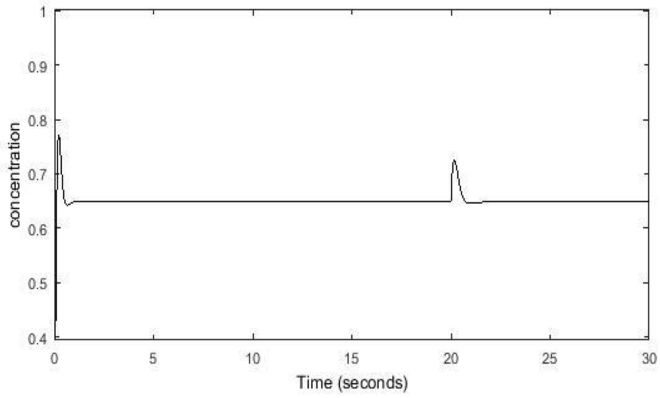

Fig.6. Performance of RC with Cold water valve bias of 0.15

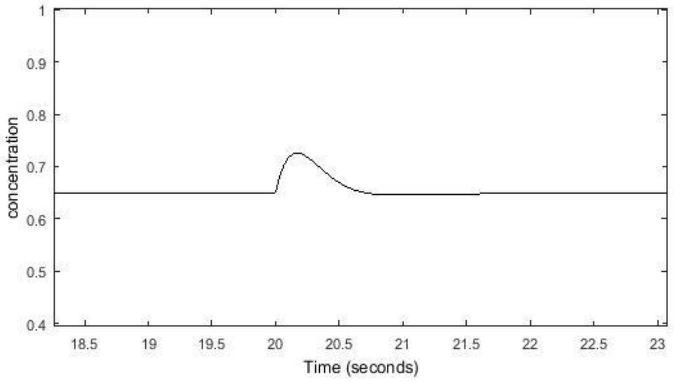

Fig.7. Detailed enlarged figure of Fig.6.

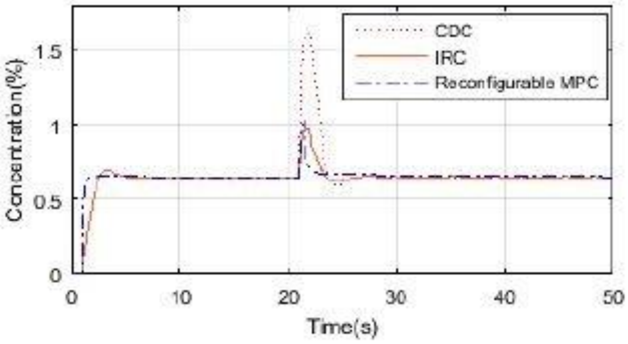

Fig.8. Output of IRC [12] with the same fault case

The liquid-level and temperature plots respectively at the above fault condition are shown below:

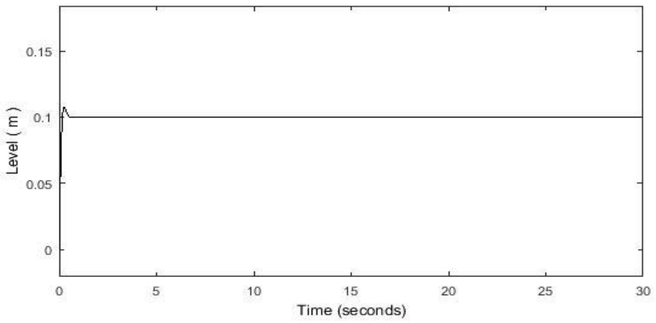

Fig 9.Liquid-Level output for the bias fault in cold water
water valve 0.15

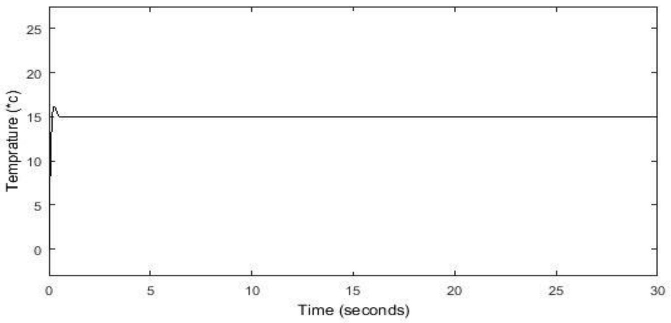

Fig 10.Output of Temperature for the bias fault in cold
valve 0.15

The figures 9 & 10 illustrate that the Reconfigurable controller providing the perfect decoupling under faulty condition than compare to the CDC and Single loop PID controller.

Experiment 2: **The fault model chosen to simulate here is offset bias fault of DMSO solution valve with o_b = 0.1, Temperature valve with o_c = 0.1** i.e. Two faults occurred simultaneously in Actuator ‘b’ and Actuator ‘c’ at t = 20s.
The experiment results shown in below figures:

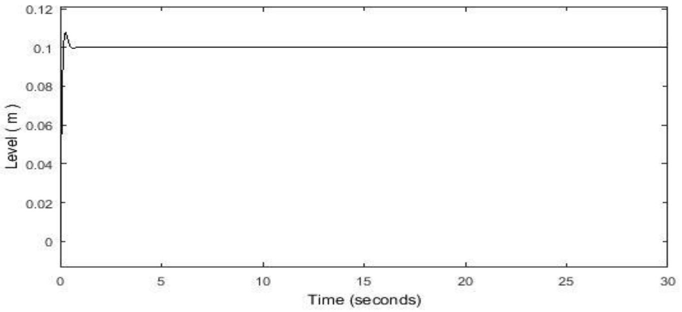

Fig. 11 Output of Liquid-Level loop

The output of the level loop resembling the perfect decoupling of the healthy level loop from faulty temperature and concentration loops.

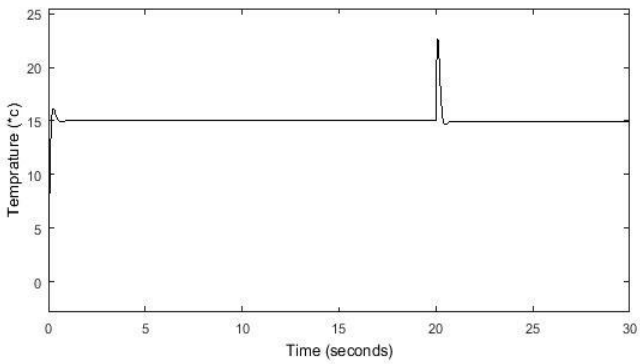

Fig. 12 Output of Temperature loop.

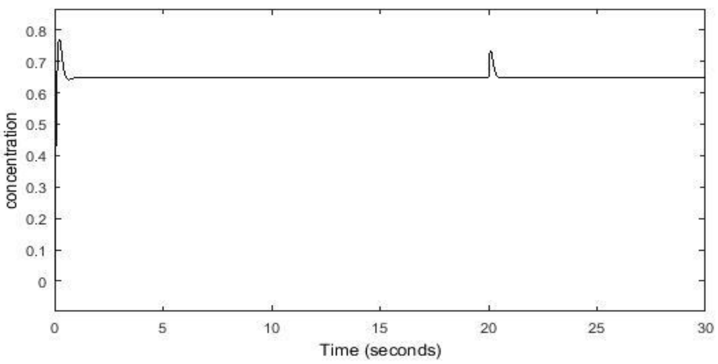

Fig. 13 Output of Concentration loop.

The above experiment results fig 12 & 13 demonstrate that, the Reconfigurable Controller stabilizing the plant for simultaneous actuator faults in less duration.

***Experiment 3:* The fault model chosen to simulate here is offset bias fault of DMSO solution valve with o_a = 0.05, Temperature valve with o_b = 0.1 and bias fault of cold water valve with o_c = 0.15** i.e. Faults occurred simultaneously in all the three actuators.

The experiment results shown in below figures:

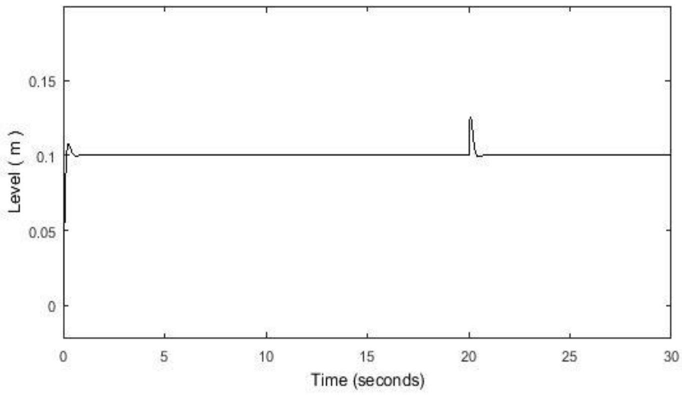

Fig. 14 Output of Liquid-Level loop.

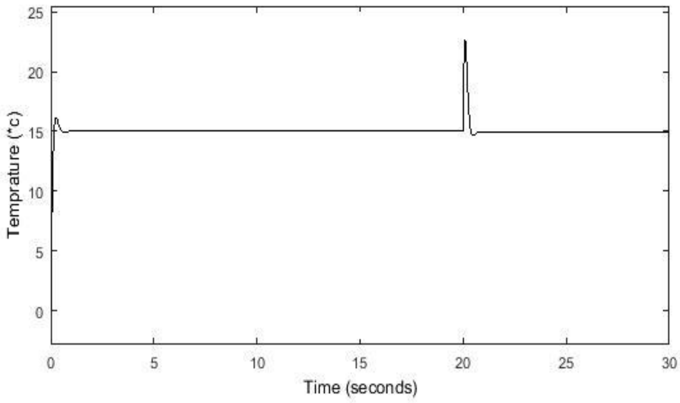

Fig. 15 Output of Temperature loop.

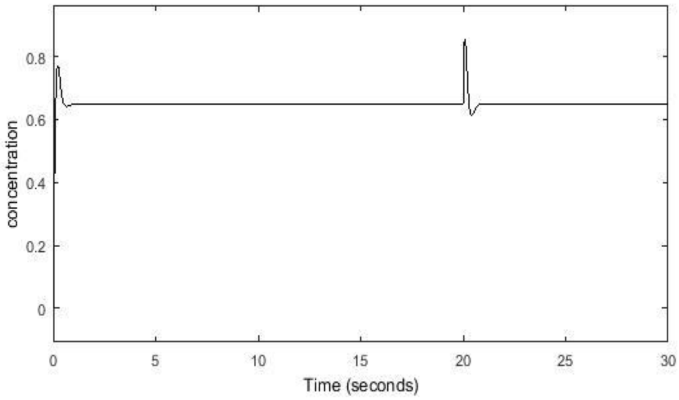

Fig. 16 Output of Concentration loop.

The above experiment results demonstrate that, the Reconfigurable Controller stabilizing the plant for simultaneous faults in all the three actuators in less duration.

V. CONCLUSION:

The Control system with fault tolerant capability is developed and simulation experiments conducted for various fault models. It is concluded from the experimental results, that is, the above approach stabilizing the plant after fault in less time than compare to other Conventional Controllers, in addition to that it is providing an excellent decoupling. It stabilizes the plant under single actuator faults as well as simultaneous multiple actuator faults also. Taking this approach to the practical applications and improving this design further such that it can tolerate all type of fault cases in any component of the plant, may be a good area of research.

REFERENCES:

1. Blanke. M., Kinnaert. M., Lunze, J., Staroswiecki, J., : diagnosis and Fault-Tolerant Contro, 2nd edn. Springer, Heidelberg (2006).
2. Y . Zhang and J. Jiang, “ Bibliographical review on reconfigurable fault – tolerant control systems,” Annu Rev. Contro, vol. 32, no.2, pp. 229-252, 2008.
3. Hassan Noura, Didier Theilliol, Jean-Christophe Ponsart, Abbas Chamseddine: Fault tolerant control systems, Springer (2009).
4. Mahmoud.M., Jiang .J., Zhang. Y., “Active Fault Tolerant Control Systems”, Springer (2003).
5. Maciejowski, J.M.,Jones, C.N. “MPC fault-tolerant flight control case study: Flight 1862. In: Proc. 5th IFAC Sympos. Fault Detection, Supervision and Safety for Techn. Processes, M1-C1,pp.121-126. Washington D.C., USA (2003).
6. Richter,J.H., Lunze, J. : Reconfigurable control of Hammerstein systems after actuator failures : stability, tracking and performance. Int. J. Control 83(8), 1612-1630 , (2010).
7. Alexandru Stancu, Eduard Codres and Vicenc¸ Puig, “A Fault Hiding Approach for the Sliding Mode Fault-tolerant Control of a Non-holonomic Mobile Robot” 2016 3rd Conference on Control and Fault-Tolerant Systems (SysTol) Barcelona, Spain, Sept. 7-9, 2016
8. Qikun Shen, Bin Jiang, Vincent Cocquempot , “ Fault-tolerant Control for T-S Fuzzy Systems with Application to Near-Space Hypersonic Vehicle With Actuator Faults”. IEEE Trans. On Fuzzy Systems, Vol.20, No.4, August-2012
9. Shengfang Dai, Yongsheng Ding, Lihong Ren, Kuangrong Hao, and Biao Huang, “A reconfigurable Control System based on Biological Immune Mechanism”, IEEE International Conference on Systems, Man and Cybernetics, San Diego ,Oct-2014.
10. Yongsheng Ding, Xiao Liang, kuang-Rong Hao and Hua-ping wang, “An intelligent Co-operative Decoupling Controller for Coagulation Bath in Polyacrylonitrile Carbon Fiber Production”, IEEE Trans. On Control System Technology, Vol.21, No.2, pp. 467-479, March 2013.
11. A . Gosh and S. K. Das, “Open-loop decoupling of MIMO plants,” IEEE Trans. Autom. Control. Vol.54, no.8, pp.1977 – 1981, Aug. 2009.
12. Yongsheng Ding, Nan Xu, Shengfang Dai, Lihong Ren, Kuangrong Hao, and Biao Huang, “ An Immune System-Inspired Reconfigurable Controller”, IEEE trans. Control Systems Technology, Vol. 24. No.5, Sept 2016.
13. Rosich. A., Puig. V., Quevedo.J “Fault-tolerant constrained MPC of PEM fuel cells. In: Proc. 46th IEE Conf. Decision and Control, pp. 2657-2662 (2007).
14. P. Cominos and N. Munro “PID Controllers: recent tuning methods and design to specification”.
15. D.-L. Yu, T.-K. Chang, and D.-W. Yu, “A stable self-learning PID control for multivariable time varying systems,” Control Eng. Pract., vol.15, no. 2, pp. 1577–1587, Feb. 2007.

★★★