A Framework for Fault-tolerant Control for an Interacting and Non-interacting Level Control System using AI

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Abstract: In chemical and process industries, interacting and non-interacting level control systems are often used for material storage and processing. The level control parameter is very vital for dealing with faults in a system (leak), actuator or sensor. System and actuator faults occurring in a system may decrease the performance or cause instability and unsafe accidents. As observed from practice, when the control performance of the interacting and non-interacting systems decreases due to occurrence of faults, a fault-tolerant control strategy (FTC) is required. This paper presents a framework for passive fault tolerant control (PFTC) using a neural network (NN) and it is designed in order to ensure the stability robustness of the system in the presence of the faults. In fact, FTC is the potential strategy which is justified by its ability to preserve an acceptable performance in the presence of faults and process disturbances. To check the effectiveness of the proposed framework single-tank and two-tank level control experimental setup are used with system and sensor faults. Simulation and experiment results are presented to demonstrate the capability of the proposed framework of PFTC using NN to counteract the effect of the system, sensor and actuator faults.

1 INTRODUCTION

Through its various potential applications, an interacting and non-interacting level control systems is one of the most used in chemical industries as well as research purpose in academics. Two-tank interacting and single-tank non-interacting level control systems are usually used in chemical processing and material handling industries to complete the various processes, so the demands of reliability, safety, and stability of the system are particularly important. This is attracting more and more attention by researchers from past two decades. Similarly, fault tolerant control strategy applied to a different multi-tank system with accommodation of sensor, actuator, and system (leak) fault in (He et al, 2017; Zhou et al, 2012; He et al, 2016; Casavola et al, 2010; Noura et al, 2000).

Over the past four decades, the complexity of a control system in industry has drastically increased due to the automation. The purpose of the complex control system is to improve control performance and system stability. However, some abnormal events occur such as faults, sensor/actuator failure, and cause damage to the system components which are not encountered at controller design level.

The fault terminology is defined according to SAFEPROCESS Technical Committee International Federation of Automatic Control (IFAC) as an unpermitted deviation of one of the characteristic property or parameter of the system from the normal condition (Isermann and Ballé, 1997). Fault-tolerant Control (FTC) is a specific strategy which has the ability to maintain acceptable performance and robustness stability in the presence of faults. In broad spectrum FTC scheme is classified into two types: one Active Fault-Tolerant Control (AFTC) and Passive Fault-Tolerant Control (PFTCS).

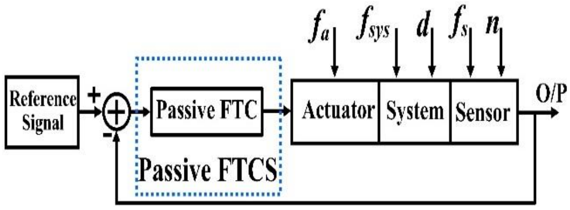

Figure 1: Architecture of a passive FTC (Patel and Shah, 2018a).

The Passive Fault Tolerant Controller is synthesized to be robust against faults, disturbances and uncertainties during the design stage. This control

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approach is designed based on full prior fault knowledge about the process faults and uncertainties using robust control tools to ensure the insensitivity of the closed loop system to the occurring faults assumed to be unknown (Patel and Shah, 2018a). The fault tolerance is achieved in PFTC by maintaining an acceptable performance and stability properties without changing the structure of the controller as shown in fig. 1, without requiring reconfiguration and without any information relating to the various failures. The suggested PFTC system subjected to actuator fault f_a, process/component fault f_{sys}, and sensor fault f_s, d is process disturbance and n is sensor noise.

As compared to the Active Fault Tolerant Control (AFTC), the PFTC has the advantage of not requiring the exact fault magnitude value and fault information, hence it is easy to implement. The PFTC can guarantee the system stability and performance after different fault occur and before the FDD or FDI phase finishes. As the possible faults have been considered at the PFTC design stage, the structures of PFTC are oftentimes fixed in the presence of different type of faults. Several PFTC methods have been proposed and have been the subject of long research. In the literature (Sadeghzadeh et al, 2012; Zhaohui and Noura, 2013; Sharifi et al, 2010; Amoozgar et al, 2012; Merheb et al, 2013) many PFTC strategies have been proposed, in presence of actuators faults, sensors faults and system/plant failures or even simultaneous failures. In (Li et al, 2015) author suggests PFTC when efficient fault diagnosis procedure is not available, however prior knowledge of the possible faults is required. (Patel and Shah, 2018b) has designed PFTC using fuzzy logic plus conventional PI controller and implemented on MATLAB (Simulink) platform with system (leak) fault and unknown process disturbance.

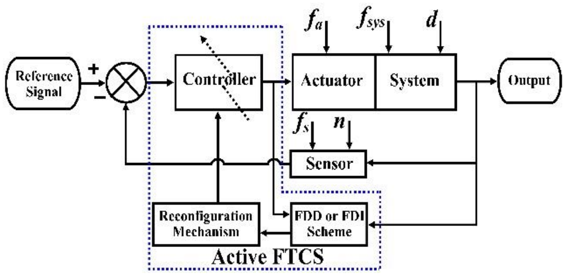

Figure 2: Architecture of an active FTCS (Gao et al, 2015).

In contrary, the AFTC system has variable controller structure as shown in fig. 2 based on supervised approaches called Fault Detection and Diagnosis (FDD) and Fault Detection and Isolation (FDI) (Gao et al, 2015). A situation like when there is no prior knowledge about the fault's type and effect on the measured process output, the FDD and FDI approaches are generally used.

The research of control mathematics for an improved performance on single-tank (non-interacting) and two-tank (interacting) level control system has been performed for several decades. The research has been encouraged by the desire to increase levels of safety, reliability, and performance of these systems, in a wide variety of demanding industrial applications. In (Orani et al, 2009), a fault detection strategy has been proposed for a three-tank system using sliding mode controller, In (Capiluppi. and Paoli, 2005) distributed fault tolerant scheme is implemented on two-tank benchmark system with faults. Authors of (Mendonca et al, 2008) have used model predictive control (MPC) and soft computing (fuzzy logic method) to design a fault tolerant control (FTC) scheme for a three-tank benchmark system with two faults. In (Basin et al, 2015) author has designed fault-tolerant algorithm and an experimental verification of FTC is conducted for a DTS200 three-tank system through varying fault sources, process disturbances, input conditions, and disturbances through inter-tank connections. In (Parikh et al, 2017) a comparison of the performance of Linear Quadratic Gaussian Control (LQG) with the Non-linear Model Predictive Control (NMPC) has been made to achieve servo plus disturbance rejection and regulatory control of a three tank system in presence of changing valve position which serves as the disturbance input.

In this paper, FTC framework is proposed for the single-tank interacting and two-tank non-interacting level process control. Neural network and PI control based passive fault tolerant controller is used in this framework to ensure the system stability and to track the desired set point (tank level or height) when an actuator, sensor, and system (i.e. tank leak) fault happens, simulations and experimental results are given using Matlab and single-tank and two-tank interacting level process experimental setup.

The remainder of this paper is organized as follows. In Section 2, the framework of PFTC and process description is explained with a mathematical model. Selected fault cases are described in subsection 3 for the non-interacting and interacting system. Subsequently, the performance of passive FTC approaches is evaluated in Sections 3 using simulation and in 4 experimental results with different faults, cases are evaluated respectively. Finally, the discussion on results and conclusions are drawn in Section 5 and 6 respectively.

2 FRAMEWORK AND PROCESS DESCRIPTION

2.1 Non-interacting Single-tank Level Process

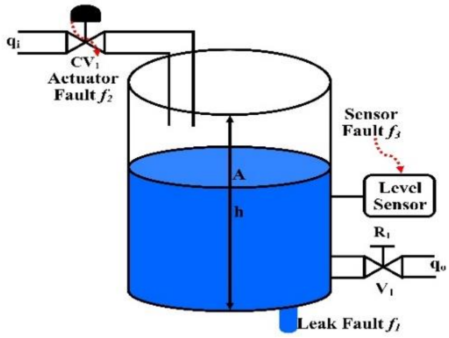

Figure 3: Single-tank non-interacting level process.

Single-tank non-interacting level process is presented in fig. 3. The process consists of one water tank, pneumatic control valve and one electric pump. The controlled variable of system is height of the tank h and manipulated variable is inlet flow q_i controlled by control valve CV_1. For the simulation the system is considered with proposed FTC scheme and without PFTCS for system (leak) and actuator faults. The process input is (inlet flow rate to tank q_i using CV_1) and the output is (tank height). The process model of the single-tank level system given by mass balance and Bernoulli's law yields:

$$A * \left(\frac{dh}{dt}\right) = (f_i - f_o) \tag{1}$$

Where,

(dh/dt) Rate of change of liquid height in tank,
A Cross section area of a tank,
f_i Inlet flow rate of a tank,
f_0 Outlet flow rate of a tank.

From the process reaction curve method obtain the model of single-tank level process is obtained as given following,

$$G_p(s) = 5/(100s + 1) \tag{2}$$

2.2 Interacting Two-tank Level Process

Two-tank interacting level process demonstrated in fig. 4. The two-tank interacting level control process comprises of two tanks and one pneumatic control valve CV_1. The system has one input flow rate q_{i1} and one output flow rate q_{o2} with interacting or disturbing flow rate q_{o3} to the second tank which is change by manual valve V_1.The system has one controlled variable second tank height h_2 which is controlled by manipulated variable inlet flow rate of first tank q_{i1} using pneumatic control valve CV_1.

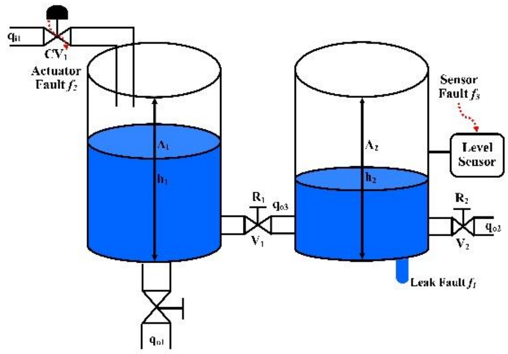

Figure 4: Two-tank interacting level process.

The process model of the two-tank level system is given by mass balance and Bernoulli's law yields:

Let $h_1$and h_2 be the fluid level in each tank, measured with respect to the corresponding outlet. Considering a simple mass balance situation, the rate of change of fluid volume in each tank equals the net flow of fluid into the tank. Thus for each of tank 1 and tank 2, the dynamic equation is developed as follows.

$$A_1\left(\frac{dh_1}{dt}\right) = (q_{i1} - q_{o1}) \tag{3}$$

$$A_2\left(\frac{dh_2}{dt}\right) = (q_{o3} - q_{o2}) \tag{4}$$

Where,

h_1, and h_2 are height of fluid in tank 1 and tank 2 respectively

A_1, and A_2 are cross sectional area of tank 1 and tank 2 respectively

q_{o3} is flow rate of fluid between tanks

q_{i1} is pump flow rate into tank 1 and tank 2 respectively

q_{o1}, and q_{o2} are flow rate of fluid out of tank 1 and tank 2 respectively.

Bernoulli's equation for a steady, non-viscous, incompressible liquid shows that the outlet flows in each tank is proportional to the square root of the head of water in the tank.

Similarly, the flow between the two tanks is proportional to the square root of the head differential.

$$q_{o1} = \alpha_1\sqrt{h_1} \tag{5}$$

$$q_{o2} = \alpha_2\sqrt{h_2} \tag{6}$$

$$q_{o3} = \alpha_3\sqrt{h_1 - h_2} \tag{7}$$

Where α_1, α_2, α_3 are proportional constants which depends on the coefficients of discharge, the cross sectional area of each tank and the gravitational constant.

Combining equation (5), (6) and (7) into both equations (3) and (4), a set of nonlinear state equations which describe the system dynamics of the coupled tank are derived as,

$$A_1\left(\frac{dh_1}{dt}\right) = \left(q_{i1} - \alpha_1\sqrt{h_1}\right) \tag{8}$$

$$A_2\left(\frac{dh_2}{dt}\right) = \left(\alpha_3\sqrt{h_1 - h_2} - \alpha_2\sqrt{h_2}\right) \tag{9}$$

For the second order configuration that shows on fig. 4, h_2 is the process variable (PV) and q_{i1} is the manipulated variable (MV). Then, equation (17) and (18) can be expressed into a form that relates the manipulated variable, q_{i1} and the process variable, h_2 and the final transfer function can be obtained as,

$$\frac{h_2(s)}{q_{i1}(s)} = \frac{k_1k_2}{T_1T_2s^2+(T_1+T_2)s+(1-k_{12}k_{21})} \tag{10}$$

By the process reaction curve method the linearized mathematical model of the two-tank interacting single input single output (SISO) level control system is as following,

$$G_{p2}(s) = \frac{56.8}{50s^2+1638s+1} \tag{11}$$

2.3 Proposed Framework of PFTC System

For the constraints like- system, sensor, and actuator faults in interacting and non-interacting level control process a new framework is proposed for FTC. For these passive FTC scheme is designed using soft computing method (neural network) NN and PI controller. It is used to detect the faults in system and gives superior closed loop control performance and stability even in presence of faults.

PFTCS gives remarkable results in the occurrence of system, sensor and actuator faults in system. The framework of PFTC is presented in fig. 5. The NN is used to incorporate the detecting the fault and overcome the consequences of the same on the system performance and stability.

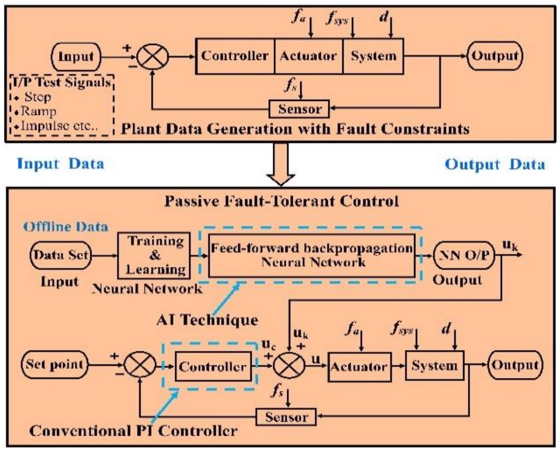

Figure 5: Proposed framework of FTCS.

PI controller transfer function is given as follows:

$$G_c = \left(K_P + \frac{1}{\tau_i s}\right) \tag{12}$$

Where,

G_c is PI controller transfer function,

K_P is proportional controller gain,

K_i is integral controller gain,

τ_i is integral time.

$$K_i = \frac{1}{\tau_i} \tag{13}$$

The PI controller parameters proportional gain K_P and Integral gain K_i are identified using manual tuning method. The gain values of the PI controller as following;

K_P= 0.8 and K_i= 0.004.

For detection of the fault in the system Feed-Forwarded Backpropagation Neural Network (FFBNN) is designed and the structure of the same presented in fig. 6. For training the FFBNN one input and one output variable chosen, at input side different fault magnitudes are taken within normalized range of [-1.7178, 1.6605] and at the output side getting controller output u_k has same normalized range [-1.7178, 1.6605].

The FFBNN is trained from different magnitude of the sensor and system faults and found the appropriate control output according to fault magnitudes. The FFBNN trained for curtain range of fault magnitudes beyond that the output of the controller is degraded gradually. The FFBNN having one hidden and one output layer. The hidden layer having 10 trained weights from input, the output having 1 layer and 10 trained weights.to the output layer.

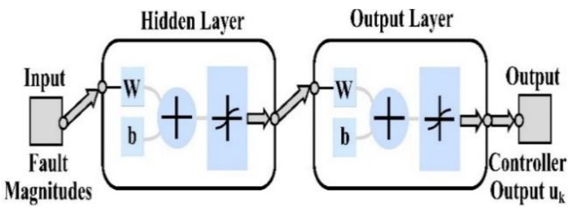

Figure 6: Internal structure of feed-forward back propagation neural network.

Performance of PFTCS and without PFTCS summarized in terms of Mean Square Error (MSE) and is defined as follows:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(\hat{X}_i - X_i\right)^2 \quad (14)$$

Where,

$\hat{X}_i$ is the vector denoting values of n number of predictions,

X_i is a vector representing n number of true values,

n are number of samples.

2.4 Justifications for the Selection of Fault Scenarios

In this paper, system (leak) fault represent situations where the tank-level reduces drastically and control valve is not able to cope with the faulty situation and hence control performance degrades. The control signal generated from controller is not sufficient to control the tank height. Actuator faults is considered as a second faults in single-tank, which represents situation where the final control element (control valve) does not opening completely and it gives lesser flow rate as compared to actual. These circumstances lead to performance deterioration.

For evaluating proposed framework of FTC for non-interacting level control process, actuator and system (leak) faults and different cases in terms of magnitude value have been chosen as shown in table 1. For designing FTC framework, conventional PI control strategy plus neural network (NN) is adopted for passive FTCSs.

Table 1: Fault scenarios taken for non-interacting level control process in simulation.

Sr. No.	**Faults Types**	**Failure details**
1.	System (leak) f_1	Tank leak at bottom (M=Magnitude value) 1. Leak fault with M= 5 2. Leak fault with M= 50 3. Leak fault with M= 100 4. Leak fault with M= 200
2.	Actuator f_2	Control valve opening with error 1. Actuator fault with M=0.5 2. Actuator fault with M= 1 3. Actuator fault with M= 2 4. Actuator fault with M= 5
3.	Sensor f_3	Control valve opening with error **NA**
4.	Beyond design basis fault ***d***	Process disturbances **NA**

3 SIMULATION RESULTS

3.1 Non-Interacting System

Fig. 7 and Fig. 8 represents the comparative results between proposed framework of FTC and without FTC on single-tank level control process with a leak and actuator fault constraint in the system. To validate the proposed framework different magnitudes of faults are simulated on the system and, error results are shown in table 2 and 3.

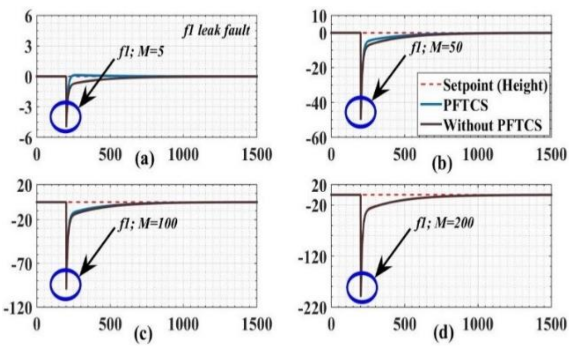

Figure 7: Comparative result of non-interacting process with system fault.

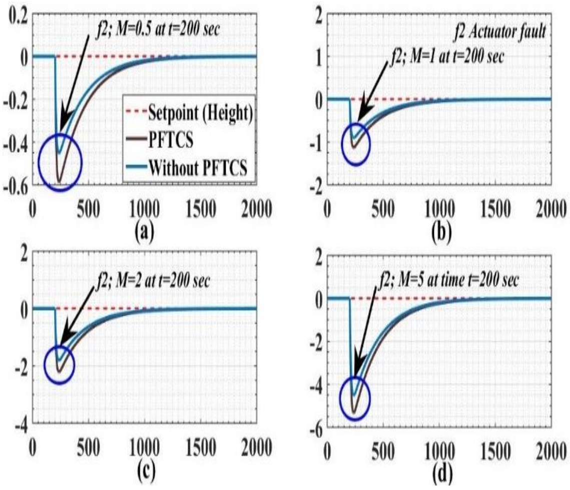

Figure 8: Comparative result of non-interacting process with actuator fault.

Table 2: PFTC framework performance comparison for system fault in non-interacting system.

Sr. No.	Controller Scheme	f_1	MSE
1.	PFTCS	M=5	0.0921
	Without PFTCS		0.1751
2.	PFTCS	M=50	13.3824
	Without PFTCS		17.5104
3.	PFTCS	M=100	61.0852
	Without PFTCS		70.0417
4.	PFTCS	M=200	261.5534
	Without PFTCS		280.1668

***f_1* denotes system fault**

Table 3: PFTC framework performance comparison for actuator fault in non-interacting system.

Sr. No.	Controller Scheme	f_2	MSE
1.	PFTCS	M=0.5	0.0156
	Without PFTCS		0.0264
2.	PFTCS	M=1	0.0625
	Without PFTCS		0.0976
3.	PFTCS	M=2	0.2499
	Without PFTCS		0.3750
4.	PFTCS	M=5	1.5617
	Without PFTCS		2.1672

***f_2* denotes actuator fault**

From observing the control performance increasing the leak fault magnitude in non-interacting level control system the performance is reducing drastically.

3.2 Interacting System

For evaluating proposed framework of FTC for interacting level control process, actuator and system (leak) faults and different cases in terms of magnitude value have been chosen as shown in table 4. For designing the FTC framework, conventional PI control strategy plus neural network (NN) is adopted for passive FTCSs. For interacting two-tank level process system (leak) fault considering in tank 1 and actuator fault considering in control valve CV_1 which control the manipulated variable inlet flow rate q_{i1}.

Table 4: Fault scenarios taken for interacting level control process in simulation.

Sr. No.	Faults Types	Failure details
1.	System (leak) ***f_1***	Tank leak at bottom (M=magnitude) 1. Leak fault with M= 5 2. Leak fault with M= 10 3. Leak fault with M= 50 4. Leak fault with M= 100
2.	Actuator ***f_2***	Control valve opening with error 1. Actuator fault with M=0.2 2. Actuator fault with M=0.5 3. Actuator fault with M= 1 4. Actuator fault with M= 2
3.	Sensor ***f_3***	Control valve opening with error **NA**
4.	Beyond design basis fault ***d***	Process disturbances **NA**

Fig. 9 and Fig. 10 represents the comparative results between proposed framework of FTC and without FTC on two-tank level control process with a leak and actuator fault constraint in the system. Table 5 and 6 clearly show that suggested framework gives better control performance in presence of system and actuator faults.

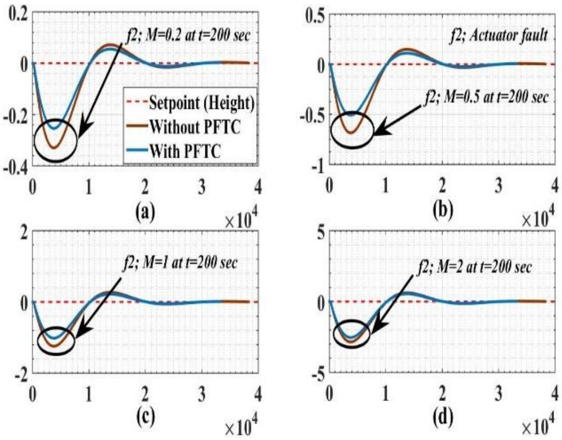

Figure 9: Comparative result of interacting process with system (leak) fault.

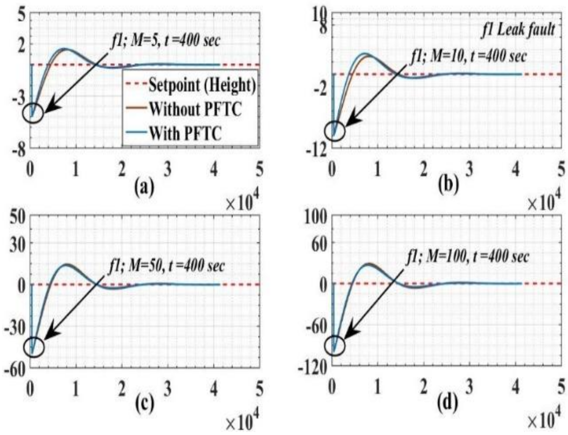

Figure 10: Comparative result of interacting process with actuator fault.

Table 5: PFTC framework performance comparison for leak fault in interacting system.

Sr. No.	Controller Scheme	f_1	MSE
1.	PFTCS	M=5	0.9031
	Without PFTCS		1.3488
2.	PFTCS	M=10	3.6344
	Without PFTCS		5.3952
3.	PFTCS	M=50	91.6850
	Without PFTCS		134.8805
4.	PFTCS	M=100	369.2292
	Without PFTCS		539.5221

f_1 denotes system fault

Table 6: PFTC framework performance comparison for actuator fault in interacting system.

Sr. No.	Controller Scheme	f_2	MSE
1.	PFTCS	M=0.5	0.0094
	Without PFTCS		0.0138
2.	PFTCS	M=1	0.0376
	Without PFTCS		0.0596
3.	PFTCS	M=2	0.1506
	Without PFTCS		0.1964
4.	PFTCS	M=5	0.9411
	Without PFTCS		1.0261

f_2 denotes actuator fault

4 EXPERIMENTAL RESULTS

4.1 Experimental Setup

Experimental setup of single-tank non-interacting level control system presented in fig. 11. PFTC strategy using AI is developed and run in the MTALAB platform. The physical system input and output are communicated to MATLAB with OPC tool. To actuate the final control element (Control valve) according to PFTC strategy control output and to get level value of the single-tank from level sensor and feedback in MATLAB software (PFTC strategy) for computing the control output, Programmable Logic Controller (PLC) is interfaced between single-tank non-interacting level control system and MTLAB software. In the non-interacting level control system the manipulated variable is in flow rate of tank 1 $q_{(i)}$ and controlled variable is tank height. One system (leak) and one sensor faults are considered to validate the proposed PFTC strategy.

Figure 11: Experimental setup for non-interacting single tank system.

To verify the effectiveness of the proposed PFTC scheme on interacting and non-interacting level control system with faulty conditions, PFTC framework is applied on real-time experimental set up of same system. To check the efficacy of framework system (leak), sensor, and actuator fault apply in different nature at different time period with change in magnitude value. A sensor fault and process disturbances are not considering at the time of experiments.

Table 7: Fault scenarios taken for non-interacting level control process in simulation.

Sr. No.	Faults Types	Failure details
1.	System (leak) f_1	Single-Tank leak at bottom **1**. Two Leak one fault with M= 4.76 to 5 from (t=275 to 350 sec) after second fault with M=11 **2**. Leak fault with M= 13.3 to M=16.4 from (t=250 to 350 sec) after M=16.4
2.	Actuator f_2	Control valve opening with error 1. Actuator fault with M=10% high value
3.	Sensor f_3	Control valve opening with error **NA**
4.	Beyond design basis fault d	Process disturbances **NA**

Figure. 12: Experimental setup for interacting two tank system.

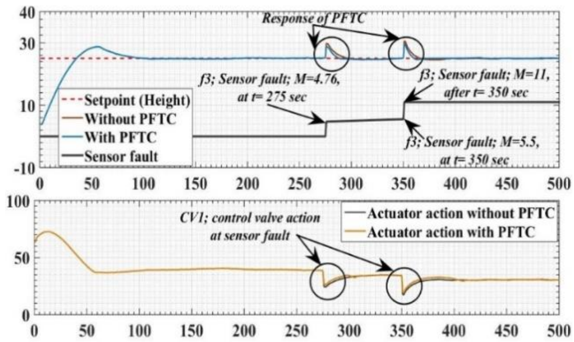

Figure. 13: Comparative experimental Comparative experimental result of non-interacting level process with multi sensor (+Ve increasing) fault.

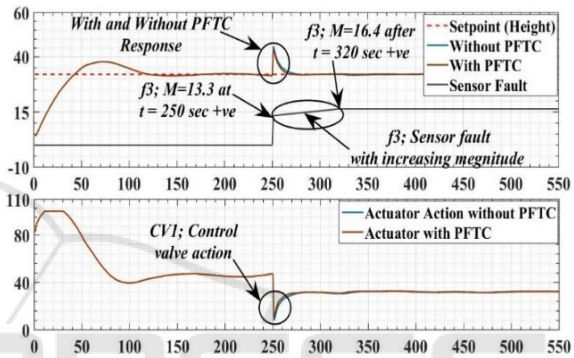

Figure 14: Comparative experimental result of non-interacting level process with multi sensor (+Ve increasing) fault.

Proposed PFTC strategy using AI is applied on experimental setup with sensor and actuator faults with deferent magnitudes in the single-tank non-interacting level control system and form observing fig. 13 to fig. 15 it clearly shows that proposed AI strategy of PFTC gives superior response as compared to without PFTC strategy. The control performance of the proposed PFTC strategy is presented in table 8 in terms of MSE error.

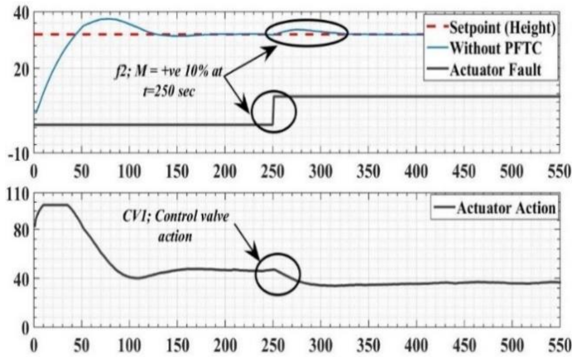

Figure 15: Comparative experimental result of non-interacting level process with actuator (+Ve) fault.

Table 8: PFTC framework performance comparison for sensor fault in non-interacting system.

Sr. No.	Controller Scheme	f_3	MSE
1.	PFTCS	Increasing fault up to M=11	6.9591
	Without PFTCS		10.7435
2.	PFTCS	Increasing fault up to M=16.4	18.0146
	Without PFTCS		20.9394

***f_3 denotes sensor fault**

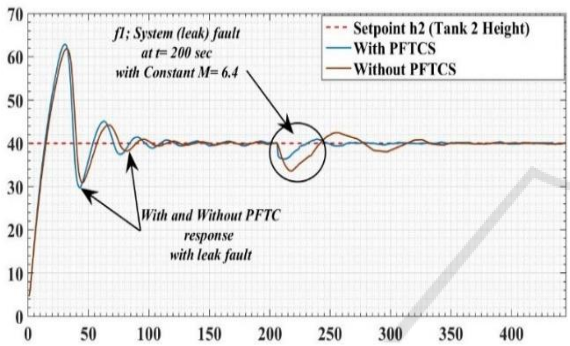

Figure 16: Comparative experimental result of interacting level process with system (leak) (+Ve) fault.

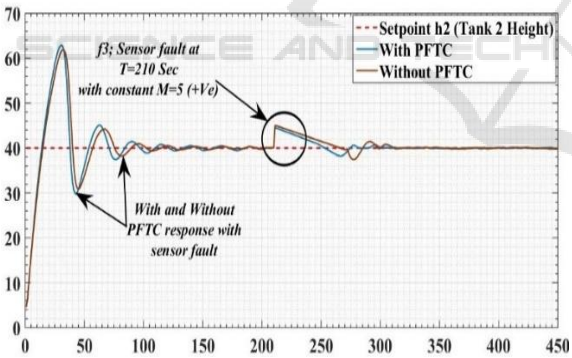

Figure 17: Comparative experimental result of interacting level process with system (leak) (+Ve) fault.

Experimental results of the two-tank interacting level control system shown in the fig. 16 and fig. 17. The sensor and leak faults are introduced in to real-time system with different magnitudes at the different times as presented in table 9. The error value shows the effectiveness of the proposed PFTC with different type of faults and magnitude. For the two-tank real-time system constant fault magnitude considered.

Table 9: PFTC framework performance comparison for system fault in non-interacting system.

Sr. No.	Controller Scheme	Fault	MSE
1.	PFTCS	f_1 M=6.4	22.4251
	Without PFTCS		30.5977
2.	PFTCS	f_3 M=5 (+Ve)	21.4513
	Without PFTCS		27.6791

***f_1 denotes system fault**
***f_3 denotes sensor fault**

5 RESULTS AND DISCUSSION

Performance of proposed framework of PFTC is applied and verified on two different processes one for non-interacting single-tank level process and a second system for interacting two-tank level process. To check the efficacy of the PFTCS with constraint of three types of faults simulation (MATLAB) platform is used. Also PFTCS is applied on real-time system and find the response with different fault types and magnitude are found. Pproposed PFTCS framework will give better control response compare to without PFTCS which are shown in terms of MSE error. The proposed framework of PFTCS scheme is capable to accommodate sensor, actuator, and system (leak) faults as shows in result figure. The main advantage of the proposed scheme is to incorporate soft computing technique (i.e. neural network) to design the controller, hence no need to find out an accurate measurement of the faults. The proposed framework has required some tuning to cope up the malfunctioning occurs at one time (i.e. all faults occurs at same time). In experimental results only leak and sensor fault are introduce on two-tank level control system. Effect of the actuator fault in same system is not explored in experiments.

6 CONCLUSION

This article attributes of the proposed framework of PFTC using conventional PI feedback controller and artificial intelligence (Neural Network) for a system (leak), actuator, and sensor faults. The proposed PFTC strategies, capable of maintaining a stability as well as control performance when a different abnormality occurs like fault and disturbances. From the observing and analyzing the simulation and real-time results, when a fault occurs the PFTC scheme using neural network plus PI controller design had achieved its desired set point and stability. Meanwhile, the PFTC using PI feedback control design achieves its desired set point but does not improve its steady state error as compared to PFTC scheme. Hence, it can be proved that proposed PFTC scheme using neural network plus PI controller mode design is one of the most efficient techniques to ensure the system performance does not degrade and set point is achieved in spite of fault and disturbances. Framework of PFTCS is a realistic choice when efficient fault diagnosis procedure is not available. However how to take into account the prior knowledge of the system faults, is a key work in the passive fault tolerant control system design. In further works PFTC scheme can be designed for multiple faults like system and sensor faults occurring at the same time. Also other than neural network another soft computing techniques can be used (e.g. Adaptive Neuro-Fuzzy Inference System (ANFIS)) for PFTC scheme.

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