Passive Fault Tolerant Control Based on Interval Type-2 Fuzzy Controller for Coupled Tank System

Himanshukumar Patel

***Abstract*—In this paper, a robust controller for a coupled tank level control is proposed in presence of actuator and system component faults. For this purpose, Interval type-2 fuzzy logic control approach (IT2FLC) technique is used to design a controller, named passive Fault Tolerant Interval Type-2 Fuzzy Controller (PFTIT2FLC) based on the robust controller to fault tolerant of coupled tank level control system. The proposed control scheme allows avoiding modeling, reducing the rules number of the fuzzy controller. The simulation results show that the PFIT2FLC can provide good tracking performance, even in presence of actuator and system component faults.**

Keywords*—*Actuator fault, system component fault, Interval type-2 fuzzy logic, fault tolerant control

I. INTRODUCTION

The actuator and system component faults in any control system may degrade performance drastically even creating dangerous situation. To tolerate such kind of unwanted situation Fault Tolerant Control (FTC) strategy is used to maintain system stability and control performance at acceptable level. The FTC classified into two broad category based on working principle. One is Active FTC and second one is Passive FTC [1]. The active FTC required separate algorithm to detect, identification and for diagnosis the fault, and based on the outcome from the algorithm controller will change the parameters [2]. Contrary the passive FTC is robust controller which designed based on predetermine faults [3].

Control design for single-tank or multiple-tank level control system with interacting and non-interacting configuration has been a topic of active research in recent years due to their important applications. The coupled-tank level control system prototype is often used in chemical processing industries and education for the design and implementation of control algorithms. In our study we consider the coupled-tank level control process laboratory setup. Because this coupled-tank has nonlinear dynamics as well interaction between two tanks, the control of this system is challenging task. Many researchers have been interested in the control of coupled-tank level system. Some of them designed trajectory tracking control strategy for double tank level process based on predictive observer [4]. The backstepping controller is design for coupled-tank level control system using adaptive high gain observer in [5], and experimental validation investigates on coupled-tank system in [6]. Also linear model predictive control (LMPC) strategy proposed for nonlinear coupled tank level control process in [7].

Since last two decade fuzzy controllers are used more and more for the controlling of coupled-tank level system. However, it is not easy to understand the organization of the fuzzy rule base, since the fuzzy rules are more complicated than the rules based on the common sense. Moreover, the number of rules is large and the complexity of the fuzzy controllers is high. In [8] authors design type-1 fuzzy logic control for coupled tank level control system, and in [9] type 2 fuzzy logic control is proposed for level control system. To accommodate the different faults like system component and actuator fault, the authors of [10] designed PFTC using fuzzy logic and conventional PI controller and reported good control performance in simulation platform with system fault and unknown process disturbance. Thereafter "in press [11]" author validate the proposed PFTC strategy from implemented on real-time single-tank non-interactive system with system fault.

The paper attributes Passive FTC using Interval Type-2 Fuzzy Logic Control (IT2FLC) for Coupled-tank Level Control System (CTLCS) subject to actuator and system component faults.

The rest of the paper is organized as follows: The dynamics of the coupled-tank level process is described in Section 2. The background of the type-2 fuzzy logic control and the design of Passive Fault Tolerant Interval Type-2 Fuzzy Logic Control (PFTIT2FLC) is presented in Section 3. The simulation results demonstrating the effectiveness of the proposed approach is presented in Section 4. A conclusion of this work is given in Section 5.

II. MODEL DESCRIPTION OF THE COUPLED-TANK SYSTEM

A. *Coupled-Tank Level Control System*

As depicted in Fig. 1 below, the CTLCS model consists of two cylindrical tanks with the same transversal area and height. The tanks are interconnected through a cylindrical pipe and have individual constant output flows. They are also equipped with two level sensors. All the flow pipes are equipped with manually adjustable valves. The design objective is to maintain the liquid level of tank 2, h_2, at a desired reference by controlling the input flow of tank 1, q_1.

The CTLCS system considered with two faults, one is system component (Tank 2 bottom leak) fault and second is actuator fault (Control Valve CV_1 choke up).

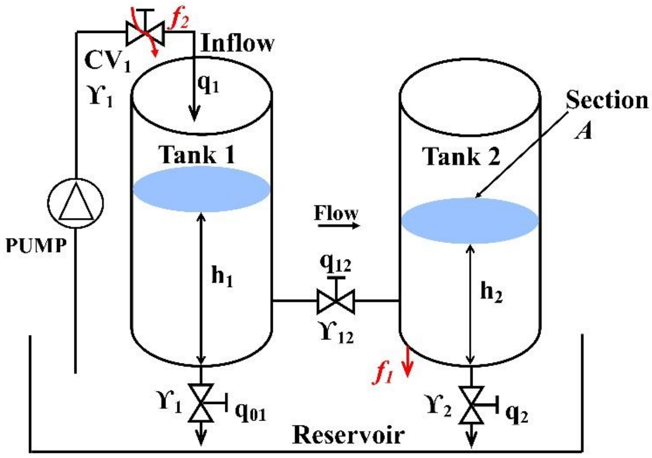

Fig. 1. Coupled-Tank level control system prototype.

B. *CTLCS Mathematical Modelling*

The modelling of the CTLCS is carried out by the Mass-Balance Equation and Bernoulli's Equation. At any instance, the rate of change of volume of liquid present inside the tank can be expressed in terms of the liquid inlet, liquid outlet and the tank interaction [2]. Mathematically,

Himanshukumar Patel,College Road, Nadiad, India

$$A_1 \frac{dh_1}{dt} = q_1 - q_{01} - q_{12} \quad (1)$$

$$A_2 \frac{dh_2}{dt} = q_{12} - q_2 \quad (2)$$

According to Bernoulli's Equation, the flow rates [2] q_{01}, q_{12} and $q2$ are given by,

$$q_{01} = \Upsilon_1 \sqrt{h_1} \quad (3)$$

$$q_2 = \Upsilon_2 \sqrt{h_2} \quad (4)$$

$$q_{12} = \Upsilon_{12} \sqrt{h_1 - h_2} \quad (5)$$

The CTLCS operating parameters and system parameters are presented in table 1:

Table 1. Coupled-tank level control system parameters.

A_1 and A_2	Area of tank 1 and Tank 2	0.0270 m^2
q_1	Inlet flow rate	0.000162 m^3/sec
Υ_1	Discharge coefficient of tank 1	6.3795
Υ_2	Discharge coefficient of tank 2	1.614
Υ_{12}	Discharge coefficient of coupling valve	4.372
h_1	Operating point of tank 1	0.35 m
h_2	Operating point of tank 2	0.31 m

The CTLCS model is linearized around the operating point using Taylor's series expansion method. The simulation is carried out with and without faults for regulatory and reference trajectory tracking control.

III. PFTIT2FLC Design And Background of Type-2 FLC

A. *Background of the type-2 fuzzy logic control*

Type-1 and type-2 fuzzy logic are mainly similar. The only essential difference between them which is the membership functions shape, besides the output process. Indeed, an interval type-2 fuzzy controller is consisting of: a fuzzifier, an inference engine, a rules base, a type reduction and a defuzzifier [12, 13] the block diagram of the type-2 FLC is presented in Fig. 2.

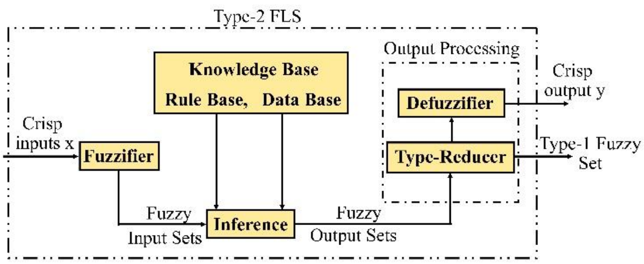

Fig. 2. Type-2 FLC structure block diagram.

(A) Fuzzifier

The fuzzifier maps the crisp input vector $(e_1, e_2 \ldots.., e_n)^T$ to a type-2 fuzzy system $\tilde{A}_x$, which very similar to the procedure performed in a type-1 fuzzy logic system.

Rules

The general form of the *i*th rule of the type-2 fuzzy logic system can be written as:

$$If\ e_1\ is\ \tilde{F}_1^i\ and\ e_2\ is \tilde{F}_2^i\ and\ \ldots\ e_n\ is\ \tilde{F}_n^i, Than\ y^i = \tilde{G}^i\ i = 1, \ldots, M \quad (6)$$

Where:

$\tilde{F}_j^i$ represents the type-2 fuzzy system of the input state *j* of the *i*th rule, x_1, x_2, …, x_n are the inputs, $\tilde{G}^i$ is the output of the type-2 fuzzy system for the rule *i*, and *M* is the number of rules. As can be seen, the rule structure of type-2 fuzzy logic system is similar to type-1 fuzzy logic system except that type-1 membership functions are replaced by their type-2 counterparts.

(B) Inference engine

In a fuzzy interval type-2 using the minimum or product t-norms operations, the *i*th activated rule $F^i(x_1, \ldots x_n)$ produces the interval that is determined by two extremes $\underline{f}^i(x_1, \ldots x_n)$ and $\overline{f}^i(x_1, \ldots x_n)$ like written below [14]:

$$F^i(x_1, \ldots x_n) = \left[\underline{f}^i(x_1, \ldots x_n), \underline{f}^i(x_1, \ldots x_n)\right] \equiv \left[\underline{f}^i, \overline{f}^i\right] \quad (7)$$

Where $\underline{f}^i and\ \overline{f}^i$ can be defined as follow:

$$\underline{f}^i = \underline{\mu}_{F_1^i}(x_1) * \ldots * \underline{\mu}_{F_n^i}(x_n) \quad (8)$$

$$\overline{f}^i = \overline{\mu}_{F_1^i}(x_1) * \ldots \overline{\mu}_{F_n^i}(x_n) \quad (9)$$

(C) Type reducer

After definition of the rules and executing the inference, the type-2 fuzzy system resulting in type-1 fuzzy system is computed. In this part, the available methods to compute the centroid of type-2 fuzzy system using the extention principle are discussed [13]. The centroid of type-1 fuzzy system A is given by:

$$C_A = \frac{\sum_{i=1}^{n} z_i w_i}{\sum_{i=1}^{n} w_i} \quad (10)$$

Where: n represents the number of discretized domain of A, $z_i \in R$ and $w_i \in [0, 1]$.

If each z_i and w_i is replaced by a type-1 fuzzy system (Z_i and W_i) , with associated membership functions of $\mu_Z(z_i)$ and $\mu_W(W_i)$ respectively, and by using the extention principle, the generalized centroid for type-2 fuzzy system $\tilde{A}$ can be expressed by:

$$GC_{\tilde{A}} = \int_{z_1 \in Z_1} .. \int_{z_n \in Z_n} \int_{w_1 \in W_1} \cdots \int_{w_n \in W_n} [T_{i=1}^{n} \mu_Z(z_i)^* T_{i=1}^{n} \mu_W(z_i)] / \frac{\sum_{i=1}^{n} z_i w_i}{\sum_{i=1}^{n} w_i} \quad (11)$$

T is a t-norm and $GC_{\tilde{A}}$ is a type-1 fuzzy system. For an interval type-2 fuzzy system, it can be written:

$$GC_{\tilde{A}} = [y_l(x), y_r(x)]$$

$$= \int_{y^1 \in [y_l^1, y_r^1]} \cdots \int_{y^M \in [y_l^M, y_r^M]} \cdots \int_{f^1 \in [\underline{f}^1 \overline{f}^1]} \cdots \int_{f^M \in [\underline{f}^M \overline{f}^M]} 1 / \frac{\sum_{i=1}^{M} f^i y^i}{\sum_{i=1}^{M} f^i} \quad (12)$$

(D) Deffuzzifier

To get a crisp output from a type-1 fuzzy logic system, the type-reduced set must be deffuzzified. The most common method to do this is to find the centroid of the type-reduced set. If the type-reduced set Y is discretized to n points, then the following expression gives the centroid of the type-reduced set:

$$y_{output}(x) = \frac{\sum_{i=1}^{n} y^i \mu(y^i)}{\sum_{i=1}^{m} \mu(y^i)} \quad (13)$$

The output can be computed using the iterative Karnik Mendel Algorithm [12]. Therefore, the deffuzzified output of an interval type-2 FLC is:

$$y_{output}(x) = \frac{y_l(x) + y_r(x)}{2} \quad (14)$$

With:

$$y_l(x) = \frac{\sum_{i=1}^{M} f_l^i y_l^i}{\sum_{i=1}^{M} f_l^i} \quad \& \quad y_r(x) = \frac{\sum_{i=1}^{M} f_r^i y_l^i}{\sum_{i=1}^{M} f_r^i} \quad (15)$$

B. PFTIT2FLC Design for coupled-tank level control system

In order to eliminate the high oscillation, nonlinear system and model uncertainty, a continuous Interval Type-2 Fuzzy logic control (IT2FLC) is used to approximate the discontinue control. The proposed control (PFTIT2FLC) scheme is shown in Fig. 2.

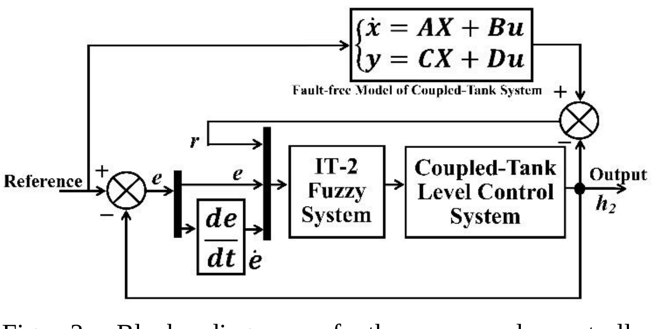

Fig. 3. Block diagram of the proposed controller PFTIT2FLC.

The IT2FLC membership functions of the fuzzy input variable are chosen to be triangular for all upper and lower membership functions. The uses labels of the fuzzy variable residue, error and its derivative are: {very small (VS), small (S), big (B), and very big (VB))}. Figure 4 presents the type-2 membership functions for the IT2FLC. The corrective control is decomposed into four levels, the IT2FLC consist of three input and one output, and so total rules can be 64.

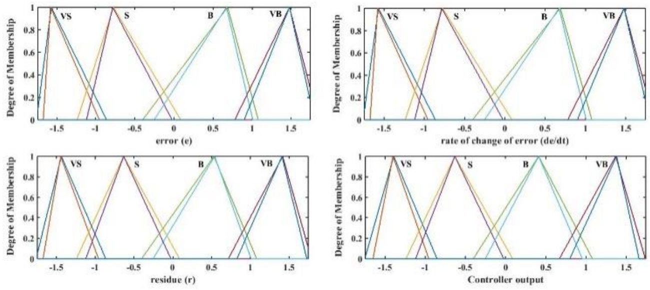

Fig. 4. Input output membership function of IT2FLC.

IV. Simulation Results

In order to verify the proposed control scheme for CTLCS subject to system component and actuator faults. First fault-free case investigate of CTLCS with proposed control scheme and compare with other control scheme. The fault-free response for various controller are presented in Fig. 5 and Fig. 6 with pulse and sine trajectory respectively.

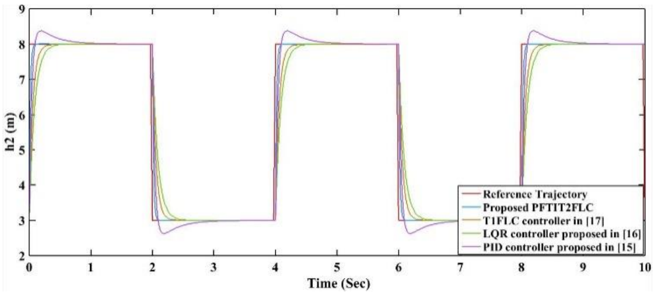

Fig. 5. Pulsed trajectory tracking response comparison without faults.

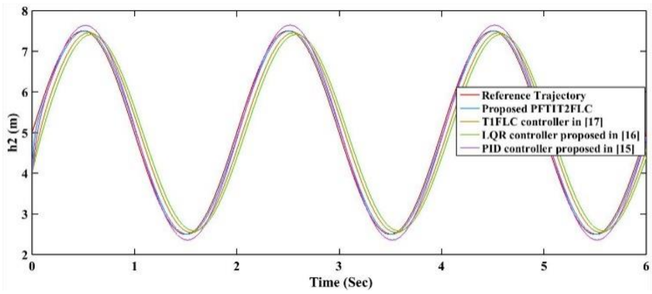

Fig. 6. Sine trajectory tracking response comparison without faults.

A. Tracking response with System component faults

Two test examining on CTLCS, test 1 is for pulsed trajectory tracking with system component faults, and test 2 is for sine trajectory tracking with system component faults with different magnitudes.

Test 1 responses with various controller depicted in Fig. 6 with system component fault f_1= 1 m and test 2 responses depicted in Fig. 7 with fault magnitude f_1= 2 m. The comparative error results also presented in table 2.

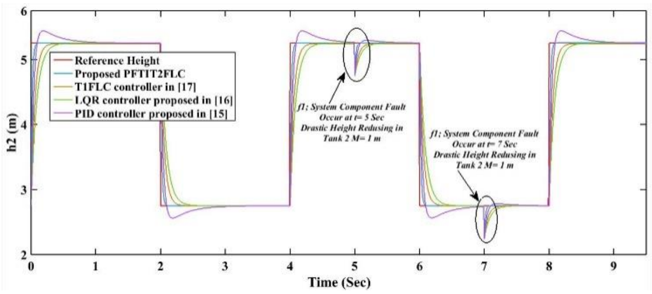

Fig. 7. Pulsed trajectory tracking response comparison with system component faults.

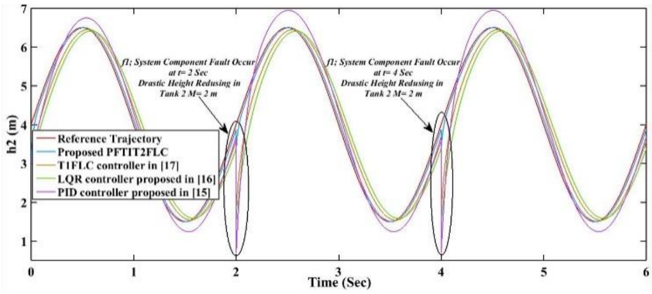

Fig. 8. Sine trajectory tracking response comparison with system component faults.

Table 2. Quantitative comparision between the proposed controller, PID controller, LQR controller and T1FLC with system component faults.

Test	**Control scheme**	**IAE**	**ISE**
		h2	**h2**
Test 1	PID Controller proposed in [15]	5.38	2.303
	LQR control proposed in [16]	3.566	1.579
	T1FLC proposed in [17]	2.31	1.577
	The proposed PFTIT2FLC	**1.023**	**0.472**
Test 2	PID Controller proposed in [15]	34.52	15.06
	LQR control proposed in [16]	6.091	5.92
	T1FLC proposed in [17]	3.27	2.105
	The proposed PFTIT2FLC	**1.672**	**0.3914**

B. Tracking response with actuator faults

Two test simulating on CTLCS, test 1 is for pulsed trajectory tracking with actuator, and test 2 is for sine trajectory tracking with actuator faults with different magnitude.

Test 1 responses with various controller depicted in Fig. 9 with system component fault f_2= 5 % and test 2 responses depicted in Fig. 10 with fault magnitude f_2= 5 %. The comparative error results also presented in table 3. The f_2 represents the control valve CV_1 choke up.

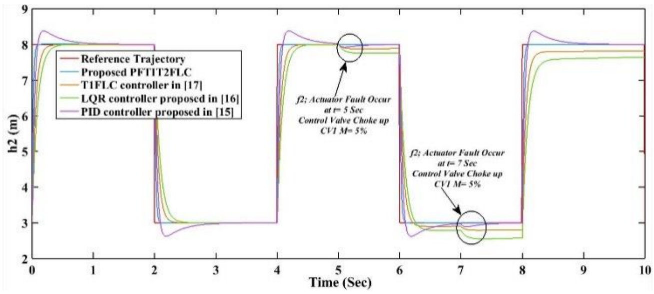

Fig. 9. Pulsed trajectory tracking response comparison with actuator faults.

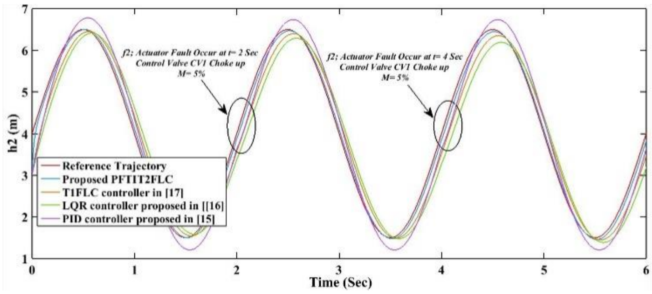

Fig. 10. Sine trajectory tracking response comparison with actuator faults.

Table 3. Quantitative comparision between the proposed controller, PID controller, LQR controller and T1FLC with actuator faults.

Test	**Control scheme**	**IAE**	**ISE**
		h2	**h2**
Test 1	PID Controller proposed in [15]	6.049	3.621
	LQR control proposed in [16]	3.698	2.175
	T1FLC proposed in [17]	2.277	1.53
	The proposed PFTIT2FLC	**1.008**	**0.4296**
Test 2	PID Controller proposed in [15]	27.34	13.84
	LQR control proposed in [16]	11.42	8.91
	T1FLC proposed in [17]	2.892	1.098
	The proposed PFTIT2FLC	**1.6898**	**0.396**

C. Regulatory step response with system component and actuator faults

The comparative regulatroy control response of the CTLCS with system componnet and actuator faults presetnted in Fig. 11 and Fig. 12. The system component fault (f_1) megnitude is M= 2 m height redusing dratically in tank 2. And two faults introdused in CTLCS with difrent time instance. Same as actuator fault (f_2) megnitude is M= 5 % Control Valve choke up in CV_1. The two faults introdused in CTLCS with difrent time instance.

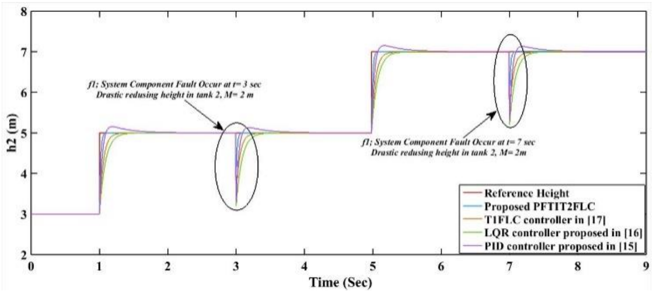

Fig. 11. Regulatory step response comparison with system component faults.

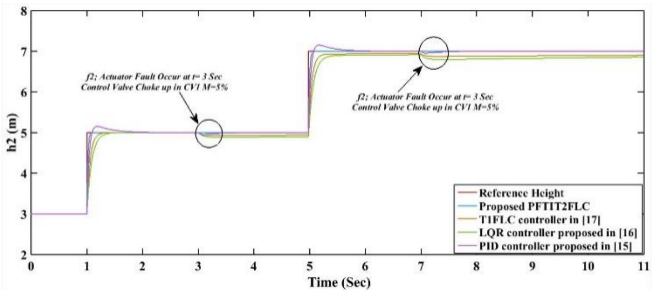

Fig. 12. Regulatory step response comparison with actuator faults.

The quantitative comparison between the proposed with other controller are presented in table 4. The ISE results shows that, lesser value of ISE for proposed controller (PFTIT2FLC) amongst other presented controller.

Table 4. Quantitative comparision between the proposed controller, PID controller, LQR controller and T1FLC with system component and actuator faults.

Test	**Control scheme**	**IAE**	**ISE**
		h_2	**h_2**
Test 1 **System Component Fault**	PID Controller proposed in [15]	0.6765	0.6165
	LQR control proposed in [16]	0.5265	0.3567
	T1FLC proposed in [17]	0.4362	0.2505
	The proposed PFTIT2FLC	**0.1527**	**0.08046**
Test 2 **Actuator Fault**	PID Controller proposed in [15]	1.572	0.5543
	LQR control proposed in [16]	1.032	0.3154
	T1FLC proposed in [17]	0.6689	0.4464
	The proposed PFTIT2FLC	**0.3054**	**0.1449**

V. Conclusion

In this paper, performances of Passive Fault Tolerant interval type-2 fuzzy logic controller (PFTIT2FLC) for coupled-tank level control system are investigated in the presence of system component (tank leak) and actuator faults. A good position tracking performance is obtained using this controller with pulse and sine reference trajectory. The simulation results have shown high efficiency of this control strategy, it maintains the stability and the good performances of the coupled-tank level control system in presence the system component and actuator faults. In addition the comparative study performed with other recent works developed in the literature, has shown the effectiveness of the proposed control approach. In the future work the general form of type-2 fuzzy sets proposed in [18, 19] will be introduced in the proposed control to increase robustness of the system and handle the uncertainty and external disturbances.

References

[1] H.R. Patel, and V. A. Shah. “Fault Detection and Diagnosis Methods in Power Generation Plants - The Indian Power Generation Sector Perspective: An Introductory Review,” PDPU Journal of Energy and Management, 2(2), pp. 31-49, 2018. ISSN 2581-5849.

[2] H.R. Patel, and V. A. Shah. “A Framework for Fault-tolerant Control for an Interacting and Non-interacting Level Control System using AI,” In Proceedings of the 15th International Conference on Informatics in Control, Automation and Robotics - Volume 1: ICINCO, ISBN 978-989-758-321-6, pp. 180-190, 2018.
DOI: 10.5220/0006862001800190.

[3] H.R. Patel, V.A. Shah,“Fault Tolerant Control Systems: A Passive Approaches for Single Tank Level Control System,” i-manager’s Journal on Instrumentation and Control Engineering, Vol. 6, no.1,pp. 11-18, 2018. doi: https://doi.org?10.26634/jic.6.1.13934

[4] G. Houssemeddine, S. Salim Hadj, and M. Faouzi “Observer-based predictive liquid level controller for a double tank process,” 7th International Conference on Modelling, Identification and Control (ICMIC 2015), IEEE, 18-20 December 2015, Sousse (Tunisia), pp. 1-6.

[5] A. Turki, S. Hadj Said, F. M'Sahli, "Backstepping Control for Two Tanks process based on Adaptive High Gain Observer", *11th International Multi-Conference on Systems Signals & Devices (SSD)*, 2014.

[6] H. Pan, H. Wong, V. Kapila, M. S. de Queiroz, "Experimental validation of a nonlinear backstepping liquid level controller for a state coupled two tank system", *Control Engineering Practice*, pp. 27-40, 2005.

[7] K. Muhammad Usman, and K. muhammad Bilal “ Liquid level control of nonlinear Coupled Tanks System Using Linear Model Predictive Control,” International Conference on Emerging Technologies (ICET 2012), pp. 1-5.
DOI: 10.1109/ICET.2012.6375434

[8] M. Abid, "Fuzzy logic control of coupled liquid tank system," in Information and Communication Technologies, 2005. ICICT 2005. First International Conference on, aug. 2005, pp. 144-147.

[9] W. Dongrui and T. Woei. “A type-2 fuzzy logic controller for the liquid-level process”, IEEE International Conference on Fuzzy Systems, IEEE, 2004, pp. 953-958 vol.2. 10.1109/FUZZY.2004.1375536.

[10] H.R. Patel, V.A. Shah, “Fuzzy Logic Based Passive Fault Tolerant Control Strategy for a Single-Tank System with System Fault and Process Disturbances,” *in Proc. 5th International Conference on Electrical and Electronics Engineering (ICEEE)*, Istanbul, Turkey, May 2018, pp. 257–262.

[11] H.R. Patel, V.A. Shah, “Performance Comparison of Passive Fault Tolerant Control Strategy with PI and Fuzzy Control of Single-Tank Level Process with Sensor and System Fault,” *Science Publications, American Journal of Engineering and Applied Sciences*, to be published.

[12] O. Castillo, P. Melin, “A review on the design and optimization of interval type-2 fuzzy controllers,” Application of Soft Computing, 12, pp. 1267-1278, 2012.

[13] J. Mendel, Uncertain rule-based fuzzy logic systems: introduction and new directions. Prentice-Hall; 2011.

[14] Q. Liang, and J. Mendel, “Interval Type-2 Fuzzy Logic Systems: Theory and Design,” IEEE Transactions on Fuzzy Systems, 8(5), pp. 535-550, 2000.

[15] D. Mukherjee, P. Kundu, and A. Gosh, “ PID controller design for an interacting tank level process with time delay using MATLABFO MCON toolbox”, 2nd International Conference on Control, Instrumentation, Energy & Communication (CIEC), IEEE, Kolkata, India, pp. 1-5, 2016. DOI: 10.1109/CIEC.2016.7513803

[16] S. Dutta, S. Seal, and A. Sengupta, “Real Time Linear Quadratic versus Sliding Mode Liquid Level Control of a Coupled Tank System”, International Conference on Devices, Circuits and Communications (ICDCCom 2014), IEEE, 12-12 September 2014, Ranchi, India, pp. 1-6, 2014. DOI: 10.1109/ICDCCom.2014.7024741

[17] D. Bhandare, and N. R. Kulkarni, “Performances Evaluation and Comparison of PID Controller and Fuzzy Logic Controller for Process Liquid Level Control”, 15th International Conference on Control, Automation and Systems (lCCAS 2015) October 13-16, 2015, Busan, South Korea, pp. 1347-1352, 2015. DOI: 10.1109/ICCAS.2015.7364848

[18] M. Mehran, and N. Marzieh, “Differentiabilityof type-2 fuzzy number-valued functions,” Communications in Nonlinear Science and Numerical Simulation, 19(3), pp. 710–725, 2014.

[19] M. Mehran, and N. Marzieh, “Type-2 fuzzy fractional derivatives,” Communications in Nonlinear Science and Numerical Simulation, 19(7), pp.2354–2372, 2014.