CERTIFICATE *Of* PARTICIPATION

Keltoum Loukal

has participated in 2nd International Conference on Engineering and Applied Natural Sciences on 15-18 October in 2022 at Konya/Turkey.

PAPER TITLE	*Fuzzy Gains-scheduled Actuator Fault-Tolerant Control Comparative Study for Two Tanks Level Systems*
PRESENTATION TYPE	*Oral*

ICEANS 2022

ICEANS 2022 CONFERENCE CHAIRMAN
Asst. Prof. Dr. Umut ÖZKAYA

Fuzzy Gains-scheduled Actuator Fault-Tolerant Control Comparative Study for Two Tanks Level System

Loukal Keltoum [1*], Abderrahmen Bouguerra [1] and Samir Zeghlache [2]

[1] LGE Research Laboratory, Department of Electrical Engineering, University Mohamed Boudiaf of M'sila, M'sila, Algeria
[2] LASS Research Laboratory, Department of Electronics, University Mohamed Boudiaf of M'sila, M'sila, Algeria

*(keltoum.loukal@univ-msila.dz)

Abstract **–** The aim of this work is to develop the actuator fault-tolerant control laws based on fuzzy logic applied to the model of a hydraulic system (tow tanks system) which is highly nonlinear. After dynamic modeling and system state modeling, we presented the theory of the two commands used in this work. First, we proposed a feedback linearization control (FLC), then we approached a synthesis of the controls with sliding mode control (SMC), The proposed methods make the hybridization between the two techniques, with the fuzzy technique, this last used to adjust the gains of the FLC and the SMC, finally a comparative study between these control laws and the performances of each and a discussion in a brief general conclusion.

Keywords – Fuzzy Logic technique, Feedback Linearization, Gains-scheduled, sliding mode control, Two Tanks System

I. Introduction

following the significant and rapid development experienced by the industrial world, hydraulic systems with coupled tanks (two tanks system) are increasingly complex and sophisticated and the diagnostic task has become essential to ensure operational safety and availability. of these systems consequently, the increase in reliability, availability and operating safety is currently one of the major concerns of manufacturers. Research in the field of fault-tolerant control and supervision and the use of already existing tools in automation, have made it possible to develop methods of dependability such as the FTC affecting the systems [1] [2].

researchers to develop new methodologies for fault diagnosis and fault tolerant control (FTC). The essential objective is to assess the impact of failures on the reliability and safety of the system so that the monitoring of these systems is effective. Indeed, an FTC is essentially based on two methods: passive FTC based on robust techniques (PFTC) [3-5], and active FTC which consists of three tasks: fault detection, Fault Isolation and fault estimation [6].

A great number of academics have absorbed their research to passive or active FTC of level system, in the case of system, actuator, or sensor faults [7], [8]. In [8], the system is distributed and estranged, rendering to an applied reasoning, into partial procedures controlled at different levels, in [9] study the proposed method must work under a control installed with its FTC connected. Some works based on fuzzy logic [10], Himanshukumar in [11] and [12] used the FTC in the case of actuator and system faults, based on the Fuzzy Logic type 1 or type 2 of three-tank system.

The control based on the feedback linearization controller (FLC is proposed by Tahir and all and Laucas and all [13] and [14] the objective is to realize the designed controller based on feedback linearization respectively. The papers of Nail et al. present a comparison betwin feedback linearization and backstepping controllers for coupled tanks system [14] [15].

The FTC based on the Sliding Mode Controller (SMC) is proposed with Rafi and Peng [16] the objective is to realize the designed controller when the fault is introduced into the equivalent control part of the SMC.

The main contribution of this paper is the comparative study between passive adaptive gains fault tolerant control of the FLC and the SMC, based on fuzzy logic application, since this controller with gains adaptation is the latest to regulate controller gains.

This article is presented as follows. Mathematical modeling of the two tanks system is presented in section 2. Section 3 explains the FTC controller based on fuzzy gains-scheduled with a FLC and a SMC control. The simulation results to validate the robustness of the proposed approaches are presented in Section 4. Finally, the conclusion in the present paper are driven.

II. MATHEMATICAL MODELLING OF THE TWO TANKS SYSTEM

The hydraulic system with coupled tanks is presented in Figure 1 [17].

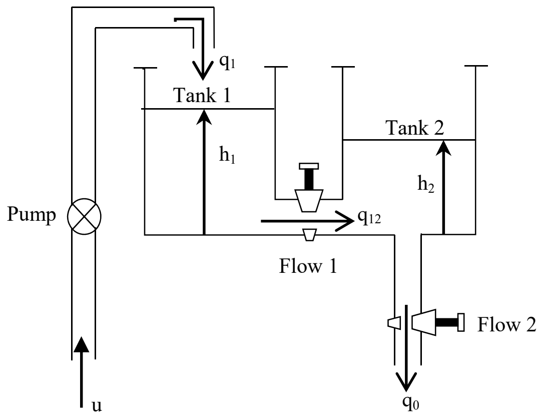


Fig. 1 Hydraulic system with coupled tanks [17].

The two dynamics equations [17], for reservoirs, are given by:

$$\begin{cases} \dfrac{dh_1}{dt} = \dfrac{1}{C}(-q_{12} + q_1) \\ \dfrac{dh_2}{dt} = \dfrac{1}{C}(q_{12} - q_0) \end{cases} \quad (1)$$

where

$$q_0 = c_2\sqrt{2gh_2} \quad (2)$$

$$q_{12} = c_{12}\sqrt{2g(h_1 - h_2)} \text{ for } h_1 > h_2 \quad (3)$$

$$c_2 = s_2.a_2 \quad (4)$$

$$c_{12} = s_{12}.a_{12} \quad (5)$$

and

$h_i(t)$: the level of the liquid in the tank i;
C : the section of the two tanks 1 and 2;
q_1 : the inlet flow generated by the pump;
q_{12} : the flow between the two tanks;
q_0 : the flow rate out of tank 2;
c_{12} : the area of the coupling orifice;
c_2 : the area of the outlet orifice;
g : the gravitation constant;
s_{12} : the channel of section 1;
s_2 : the channel of section 2;

a_{12}, a_2 the discharge coefficients of valve 1 and valve 2, respectively. Finally, the nonlinear differential equation of the hydraulic system is given by:

$$\begin{cases} \dfrac{dh_1}{dt} = \dfrac{1}{C}(-s_{12}.a_{12}\sqrt{2g(h_1 - h_2)} + k_p.u) \\ \dfrac{dh_2}{dt} = \dfrac{1}{C}(s_{12}.a_{12}\sqrt{2g(h_1 - h_2)} - s_2.a_0\sqrt{2gh_2}) \end{cases} \quad (6)$$

$$y = h_2 \quad (7)$$

with

y : the output of the system.

where

$$u = \begin{cases} u_{\max} & if \quad u \geq u_{\max} \\ 0 & if \quad u \leq 0 \end{cases} \quad (8)$$

For this system, we define the state model [16msila], with

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} h_2 \\ h_1 \end{bmatrix} \quad (9)$$

such as

$$x = \begin{cases} \dot{x}_1 = \alpha_1.\sqrt{x_2 - x_1} - \alpha_2.\sqrt{x_1} \\ \dot{x}_2 = -\alpha_1.\sqrt{x_2 - x_1} + k_c.u \end{cases} \quad (10)$$

$$y = x_1 \quad (11)$$

and

$$\alpha_1 = \frac{s_{12}.a_{12}\sqrt{2g}}{C}; \alpha_2 = \frac{s_2.a_2\sqrt{2g}}{C}; k_c = \frac{k_p}{C}$$

III. FEEDBACK LINEARIZATION CONTROL DESIGN

Consider a system (10), defined by the following nonlinear state representation:

$$\begin{cases} \dot{x} = f(x) + g(x).u \\ y = h(x) \end{cases} \quad (12)$$

With u is the control vector (input), y is the output vector, $f(x)$ and $g(x)$ are the vector fields respectively and $h(x)$ is the output. If we consider the case of systems with m inputs and m outputs, we seek a static loop of the form:

$$u = \alpha(x) + \beta(x)v \tag{13}$$

we have four steps to calculate the control law:

- choice of system output quantities,
- calculation of vector relative degree and change of coordinates,
- non-linear state feedback,
- Asymptotic stability and reference tracking.

A. Step 1: Relative Degree Calculation

In our case, the commands appear for the first time in the second derivatives:

$$\begin{cases} y = h(x) = x_1 \\ y^{(1)} = h_1(x) = L_f h(x) = \dot{x}_1 = \alpha_1.\sqrt{x_2 - x_1} - \alpha_2.\sqrt{x_1} \\ y^{(1)} = \alpha_1.\left(x_2 - x_1\right)^{0.5} - \alpha_2.x_1^{0.5} \\ y^{(2)} = h_2(x) = L_f^2 h(x) = 0.5.\alpha_1.\left(\dot{x}_2 - \dot{x}_1\right)\left(x_2 - x_1\right)^{-0.5} \\ \quad -0.5.\alpha_2.\dot{x}_1 x_1^{-0.5} \\ y^{(2)} = 0.5.\alpha_1.(-\alpha_1.\left(x_2 - x_1\right)^{0.5} + k_u.u - \alpha_1.\left(x_2 - x_1\right)^{0.5} \\ \quad -\alpha_2.x_1^{0.5})\left(x_2 - x_1\right)^{-0.5} - 0.5\alpha_2(\alpha_1.\left(x_2 - x_1\right)^{0.5} \\ \quad -\alpha_2.x_1^{0.5})x_1^{-0.5} \end{cases} \tag{14}$$

We note, for this output, a relative degree, r=2.

B. Step 2: Calculate of the Diffeomorphism

Diffeomorphism is used to transform a nonlinear system into another nonlinear system with performing a change of variables of the form:

$$\begin{cases} z_1 = \phi_1(x) = h(x) = x_1 \\ z_2 = \phi_2(x) = L_f h(x) = \dot{x}_1 = \alpha_1.\left(x_2 - x_1\right)^{0.5} - \alpha_2.x_1^{0.5} \\ z_3 = \phi_3(x) = L_f^2 h(x) = \dot{x}_1 = 0.5.\alpha_1.[(-\alpha_1\left(x_2 - x_1\right)^{0.5} \\ \quad + k_u.u - \alpha_1.(x_2 - x_1)^{0.5} + \alpha_2.x_1^{0.5})\left(x_2 - x_1\right)^{-0.5}] - \\ \quad 0.5.\alpha_2(\alpha_1\left(x_2 - x_1\right)^{0.5} + \alpha_2.x_1^{0.5})x_1^{-0.5} \end{cases} \tag{15}$$

C. Step 3: Controller Design using Pole Placement

The control law which converts the nonlinear model of the system (15) into an exact linear representation is given by:

$$\begin{cases} \dot{z}_1 = z_2 = \dot{x}_1 \\ \dot{z}_2 = z_3 = 0.5.\alpha_1.[(-\alpha_1\left(x_2 - x_1\right)^{0.5} \\ \quad + k_u.u - \alpha_1.(x_2 - x_1)^{0.5} + \alpha_2.x_1^{0.5})\left(x_2 - x_1\right)^{-0.5}] \\ \quad -0.5.\alpha_2(\alpha_1\left(x_2 - x_1\right)^{0.5} + \alpha_2.x_1^{0.5})x_1^{-0.5} = v \end{cases} \tag{16}$$

where

$$\begin{cases} u = \dfrac{\begin{gathered}(v + \alpha_1^2 - 0.5.\alpha_1.k_u.u(x_2 - x_1)^{-0.5} - 0.5.\alpha_2^2 \\ +0.5.\alpha_1.\alpha_2.x_1^{-0.5}(x_2 - x_1)^{0.5})\end{gathered}}{0.5.\alpha_1.k_u.\left(x_2 - x_1\right)^{-0.5}} \\ v = -k_1.z_1 - k_2.z_2 \end{cases} \tag{17}$$

IV. SLIDING MODE CONTROL DESIGN

Sliding mode control or is a technique based on the commutation of state variable functions used to create a variety or a hyper sliding surface obtained by the cancellation of a chosen sliding surface [18], [19].

A. 1st Step: Choice of the Sliding Surface

The linear form of the sliding surface is as follows:

$$s(x) = \sum_{i=1}^{i=n} \lambda_i\, e_i \tag{18}$$

The nonlinear surface is that of Slotine [20] and is written in the following form:

$$s = \left(\frac{d}{dt} + \lambda\right)^{n-1} \tag{19}$$

we define the Lyapunov function by:

$$V(x) = \frac{1}{2} S(x)^2 \tag{20}$$

To guarantee the stability of the system, we will choose the Lyapunov function in a way that decreases over time, so the conditions given by:

$$\dot{V}(s) = s.\dot{s} < -k.|s| \quad ou \quad \dot{V}(s) < -k.sign(|s|) \tag{21}$$

B. 2nd Step: Calculates the Control Law

The command is given by:

$$u = u_{eq} + u_{att} \tag{22}$$

V. Fuzzy Gains-scheduled FTC of the FLC and the SMC of the Two Tanks System

The fuzzy Gains-scheduled Controller (FGSC) is used to tune the gains online of the FLC and the SMC where the tracking error is used to determine the control parameters, a set of linguistic rules is used in the fuzzy gain adaptive structure:

$$if\ e(k)\ is\ A_i\ then\ K_{1FLC}\ , K_{2FLC}\ \&\ K_{SMC}\ is\ B_i\ \ , C_i\ and\ D_i \tag{23}$$

The membership functions for the input is defined with the Gaussian shapes (Figure 2), and the output variables with the singleton shapes (Figure 3).

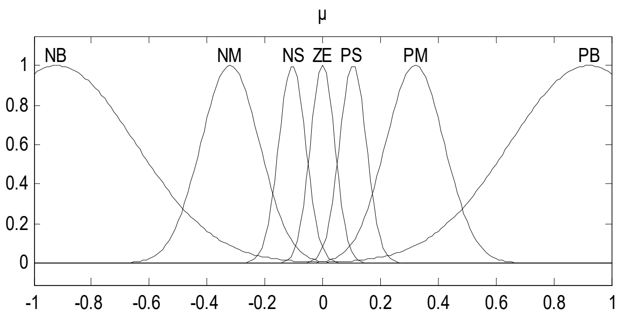


Fig. 2 Membership function for the input.

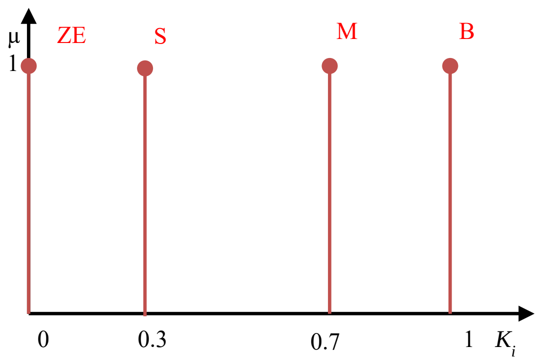


Fig. 3 Membership function for the outputs (the gains).

The configuration of the proposed method fuzzy gains-scheduled of the FLC and the SMC structure is exposed in Figure 4.

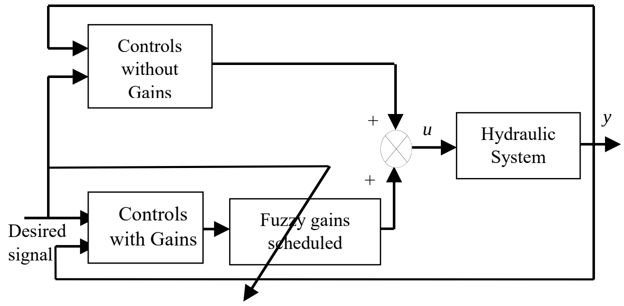


Fig. 4 Fuzzy gains-scheduled of the FLC and the SMC structure.

The actuator fault is assumed to be additive and modeled by an increase of $H\%$ in the control signals *rect*. We assume that the fault appears at time t = 300 s and disappears at time t = 310 s (Figure 5).

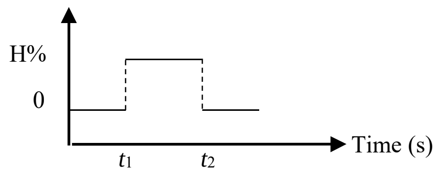


Fig. 5 Type of the actuator fault added to command *u*.

The function can be considered as a signal:

$$f_a(t) = H.rect(\frac{t-\tau}{T}) \tag{24}$$

such as

$rect$: is the rectangular function;

H : is the amplitude;

T : is the fault duration;

τ : is the center of the rectangular function $rect$;

u : is the step function, with $t_2 > t_1$.

VI. Simulation Results

Table 1 show the parameters of the coupled tanks:

Table 1. The parameters of the coupled tanks [17].

Definition	Parameter	Value
Section of each tank	*C*	9350.10-6 m^2
Section of the variable opening of each valve	s_{12}	78.5. 10-6 m^2
	s_2	78.5. 10-6 m^2
Discharge coefficient	c_{12}	1
	c_2	0.6
Pump gain	k_p	450.10-6 m^3 /*s.v*
Sensor gain	k_s	41 *v/m*
The gravitation constant	*g*	9.81 m/sec^2

The results of the simulation are given in Figures 7, 8 and 9, and the evolution of the actuator faults is given in Figure 6.

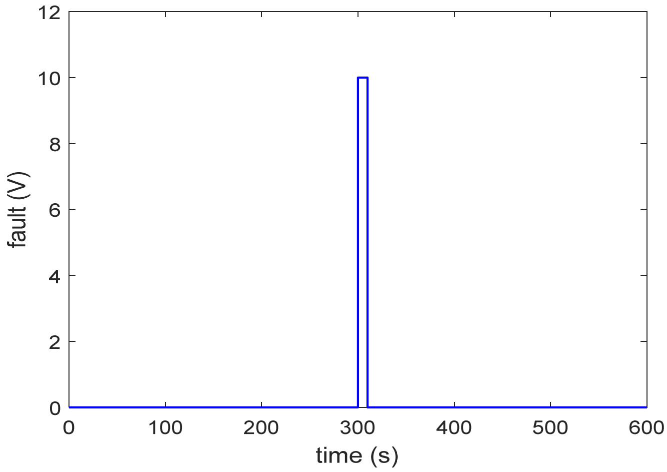
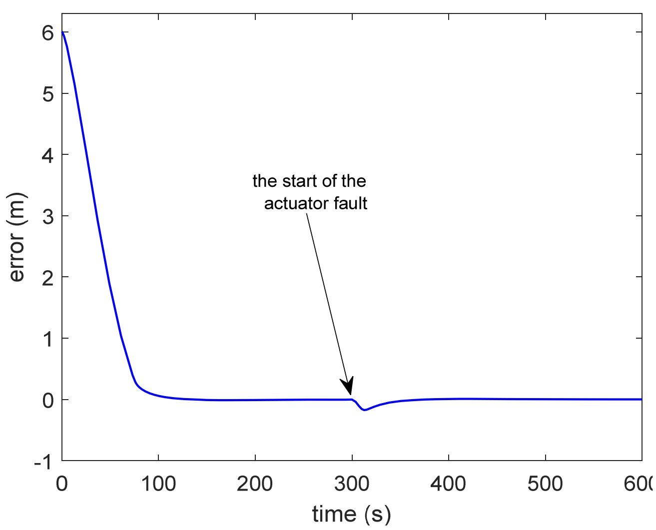
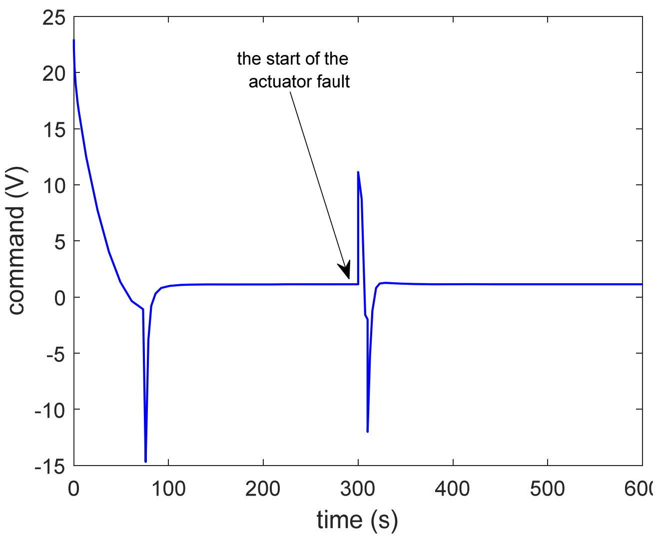


Fig. 6 The actuator fault.

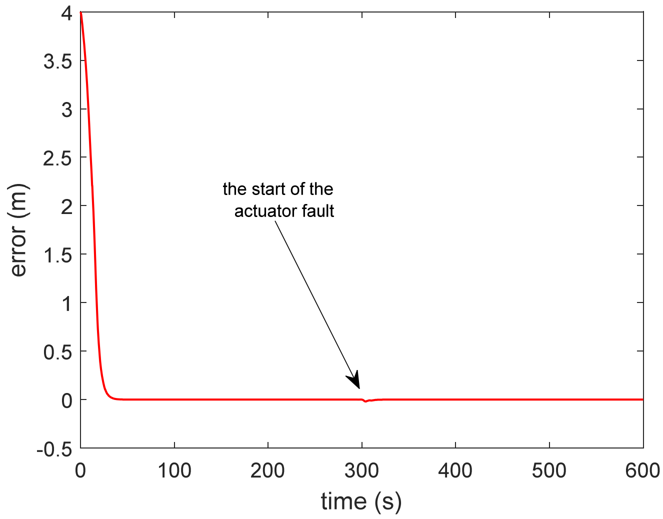


(a) The error of the FLC.

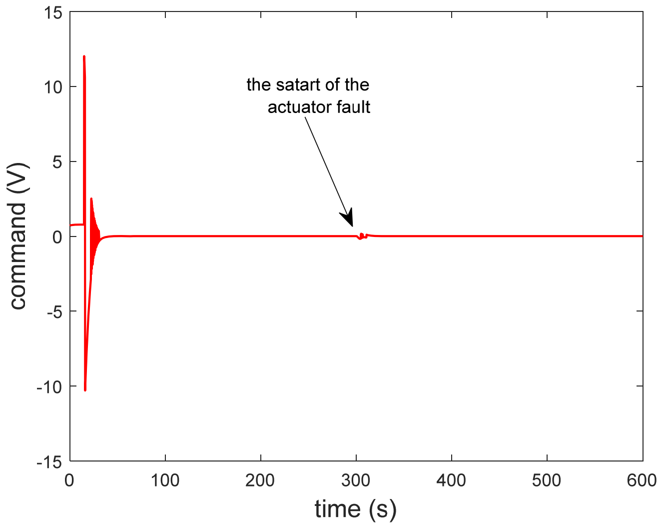


b) The command of the FLC.

Fig. 7. Simulation results of the FLC with actuator faults.



(a) The error of the SMC.



(b) The command of the SMC

Fig. 8 Simulation results of the SMC with actuator faults.

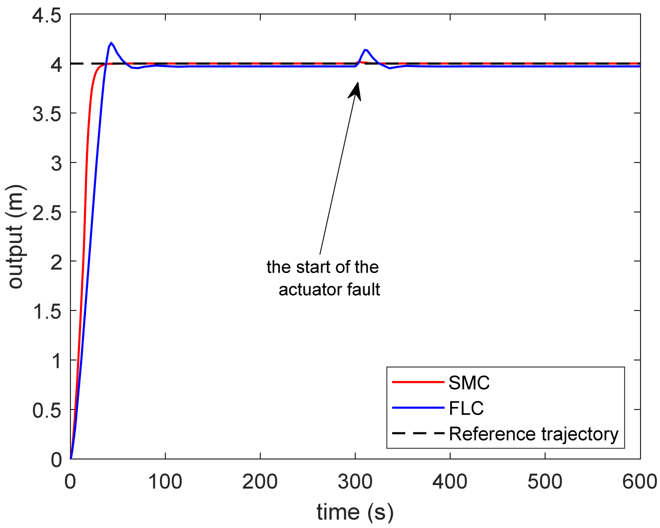


Fig. 9 Comparison between the proposed controllers: the SMC and the FLC with actuator faults.

VII. DISCUSSION

From figures 7, 8 and 9 we notice that when the actuator fault injected, the regulation and following errors are low and that there is a good tracking of the desired trajectories. Compared with the FLC, oscillations with large amplitude are observed, we can see also that when the actuator faults occur, the value of the gains decreases to avoid the overshoot which may be caused by the increase in command.

VIII. CONCLUSION

The work presented in this paper summarizes the control of a two tanks system based on the fuzzy gains-scheduled in the presence of an actuator fault. This involves developing an adaptive gains k_1 and k_2 of the FLC and the gain k of the SMC using fuzzy logic in order to ensure tracking performance in the case of fault addition, the SMC presents good performances when compared with the FLC.

REFERENCES

[1] A. El Moussati, K. Kpalma, M. G. Belkasmi, M. Saber and S. Guégan, Advances in Smart Technologies Applications and Case Studies. Lecture Notes in Electrical Engineering, vol. 684, Springer Nature Switzerland, 2020.

[2] D. Jude Hemanth, V. D. Ambeth Kumar, S. Malathi, O. Castillo and B. Patrut, Emerging Trends in Computing and Expert Technology. Lecture Notes on Data Engineering and Communications Technologies, vol. 35, Springer Nature Switzerland, 2020.

[3] L. Wang, W. Zhang, and X. Li, "Fuzzy Iterative Learning Fault Tolerant Control for Batch Processes with Different Types of Actuator Faults", In: IEEE CAA Symposium on Fault Detection, Supervision, and Safety for Technical Processes, Chengdu, China, pp. 1-6, 2021.

[4] H. R. Patel and V. A. Shah, "Passive Approach for Fault Tolerant Controller Using Hybrid Controller Structure for Effective Level Control of Conical Tank System", Journal of Mathematics and Statistics, Vol. 6, No. 1, pp. 35-46, 2020.

[5] H. R. Patel and V. A. Shah, "A Passive Fault-Tolerant Control Strategy for a Non-Linear System: An Application to the Two Tank Conical Non-Nnteracting Level Control System", MASKAY, Vol. 9, No. 1, pp. 1-8, 2019.

[6] L.F. Mendonc, J. M. C. Sousa, "Fault Accommodation of an Experimental Three Tank System Using Fuzzy Predictive Control", In: IEEE International Conference on Fuzzy Systems, Hong Kong, China, pp. 1619-1625, 2008.

[7] H. R. Patel and V. A. Shah, "Passive Fault Tolerant Control System Using Feed-forward Neural Network for Two-Tank Interacting Conical Level Control System Against Partial Actuator failures and Disturbances", IFAC-Papers On Line, Vol. 52, No. 14, pp. 141-146, 2019.

[8] S. Raval, H. R. Patel and V. A. Shah, "Fault-Tolerant Controller Comparative Study and Analysis for Benchmark Two-Tank Interacting Level Control System", SN Computer Science, Vol. 2, No. 1, pp. 1-10, 2021.

[9] A. G. A. M. Mohammed, H. A. Sirag, S. D. A. A. Alkareem and M. B. M. Amien, "Design of Fault Tolerant Control System(strategy) for Two Water Tanks", International Conference on Computer, Control, Electrical, and Electronics Engineering, Khartoum, Sudan, pp. 1–6, 2018.

[10] M. Bahita, and K. Belarbi, "Real Time Application of a Fuzzy Adaptive Controller to Level Control in a Tank", In: 12th International conference on Sciences and Techniques of Automatic control & computer engineering, Sousse, Tunisia, pp. 792-800, 2011.

[11] R. B. Kearfott, I. Batyrshin, M. Reformat, M. Ceberio and V. Kreinovich, Fuzzy Techniques: Theory and Applications, Proceedings of the 2019 Joint World Congress of the International Fuzzy Systems Association and the Annual Conference of the North American Fuzzy Information Processing Society, Springer Nature Switzerland, 2019.

[12] H. R. Patel and V. A. Shah, "Fault Tolerant Control Design Based on Takagi-Sugeno Fuzzy Logic: Application to a Three-Tank System", In: 11th Conference of the European Society for Fuzzy Logic and Technology, Prague, Czech Republic, pp. 256-266, 2019.

[13] L. Oliveira, A. Bento, V. J. S. Leite and F. Gomide, "Evolving Granular Feedback Linearization: Design, Analysis, and Applications", Applied Soft Computing Journal, vol. 86, pp. 1–33, 2020.

[14] F. Tahir, N. Iqbal and G. Mustafa, "Control of a Nonlinear Coupled Three Tank System using Feedback Linearization", Third International Conference on Electrical Engineering, pp. 1–6, Lahore, Pakistan, 2009.

[15] G. E. Kumar and J. Arunshankar, "Control of Nonlinear Two-Tank Hybrid System Using Sliding Mode Controller with Fractional-Order PI-D Sliding Surface", Computers and Electrical Engineering, vol. 2017, pp. 1-13, 2017.

[16] H. Delavari, A. R. Noiey, "Genetic-based Fuzzy Sliding Mode Control of an Interconnected Twin-Tanks", In: The International Conference on "Computer as a Tool, Warsaw, Poland, pp. 714-719, 2007.

[17] A. Boubakir, F. Boudjema, C. Boubakir, N. Ikhlef, "Loi de Commande par Mode de Glissement avec Une Surface de Glissement Non Linéaire Appliquée au Système Hydraulique à Réservoirs Couplés", 4th International Conference on Computer Integrated Manufacturing, Setif, Algeria, pp. 1-6, 2007.

[18] S. Zeghlache, K. Kara, D. Saigaa, "Fault Tolerant Control Based on Interval Type-2 Fuzzy Sliding Mode Controller for Coaxial Trirotor Aircraft", ISA Transactions, Vol. 59, No. 1, pp. 215-231, 2015.

[19] L. Jinkun, and W. Xinhua, Advanced Sliding Mode Control for Mechanical Systems Design, Analysis and MATLAB Simulation, 1st edition, Tsinghua University Press, Beijing and Springer-Verlag Berlin Heidelberg, 2011.

[20] J. J. E. Slotine, and W. Li, Applied Nonlinear Control, Englewood cliff, new Jersey, Prentice Hall, 1991.