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COMPARISON OF FUZZY LOGIC CONTROLLERS FOR A MULTIVARIABLE PROCESS

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Abstract— The Interval Type-2 Fuzzy Logic Controller (IT2FLC) for a Quadruple Tank Process (QTP) is demonstrated in this paper. Here the Interval Type-2 based Fuzzy membership function is used. The QTP is made to operate in minimum phase mode. The vertices of fuzzy membership functions are tuned with IT2FLC to minimize Integral Absolute Error. Performance of IT2FLC and Type-1 Fuzzy Logic Controller (T1FLC) are compared with decentralized PI controller, by simulation using MATLAB/Simulink. Simulation results show that satisfactory performance for both servo and regulatory responses.It has been observed that dynamic performance of IT2FLC is better than the other two controllers. Moreover, compared with the T1FLC controller, IT2FLC performs better, particularly in noisy environments.

Keywords— *Quadruple Tank Process, Decentralized PI, Type 1 Fuzzy Logic Controller, Interval Type 2 Fuzzy Logic Controller.*

I. INTRODUCTION

The multivariable laboratory process, called the Quadruple Tank Process (QTP), consists of four interconnected liquid tanks, two pumps and two valves, [1] and is shown schematically in Fig. 1. The inputs are the voltages to the two pumps (v_1, v_2) and the outputs are the liquid levels in the lower tanks (h_1, h_2). The linearized dynamics of the process exhibits a multivariable zero that can be moved from one side of the complex plane to the other one by changing the valves positions γ_1 and γ_2. This process is found to be ideally suited to illustrate many concepts in multivariable control.

Luyben [2] presented a large number of genuine multi-loop control system, which are made up of Single-Input/Single-Output (SISO) controllers acting in a multiloop fashion. Designing of multivariable decoupling and multi-loop PI/PID controllers in a sequential manner are developed by Shiu and Huang [3]. The method is based on a single-loop tuning techniques developed for multivariable systems with unknown dynamics. Tan et al [4] proposed simple tuning rules for both stable and integrating processes based on loop-sharing H_∞optimal control. Zhuang and Atherton [5] designed a diagonal PID controller tuning using an integral performance optimization procedure for a Two Input Two Output (TITO) system. The characteristic locus method usually results in better step response than the generalized Ziegler-Nichols method. Jerry M. Mendel [6] presented IT2FLC and provided its advantage over Type-1 Fuzzy Logic. Also, IT2FLS models can handle higher levels of uncertainty and thus opens up an efficient way of developing improved control systems and for modeling human decision making. Oscar Castillo et al [7] designed the fuzzy Lyapunov synthesized system that is stable and robust. Also the IT2FLC membership functions can perturb or change the definition domain of the Footprint of Uncertainty (FoU) without losing the stability of the controller. Wu et al [8] explained the five uncertainty measures for IT2Fs-centroid, cardinality, fuzziness (entropy), variance and skewness are stated. Formulae for computing these measures were also obtained. Wu et al [9] designed a GA-based T2FLC for the coupled-tank liquid-level process and proved the robustness of T2FLC which outperforms T1FLC. Hani Hagras [10] applied IT2FLC to coupled tank liquid level system showed that copes well than T1FLC. Deepa et al [11] applied a decentralized PI controller and tuned the PI parameters using bacteria foraging and computed the performance index Integral Square Error (ISE). Suja Mani Malar [12] et al compared the performances of soft computing techniques such as Neural Networks, Fuzzy Logic and Adaptive Neuro Fuzzy Inference system (ANFIS).

The outline of the paper is as follows. Nonlinear and linearized model of QTP is presented in section 2. Control techniques are discussed in section 3, 4 and 5. Simulation results and conclusions are presented in sections 6 and 7 respectively.

II. MODEL OF QUADRUPLE TANK PROCESS

The schematic diagram of the Quadruple Tank Process is shown in Fig.1 and its laboratory setup is shown in Fig.2. Process signals from the four tank level transmitters are interfaced with computer. Control algorithm running on the computer sends outputs to the individual control valves through interfacing units. Tanks 1 and 2 are mounted below the other two tanks for receiving water flow by gravity. Each tank outlet opening is fitted with a valve. Both pumps 1 and 2 take suction from the supply tank. Discharge from pump 1 is split between tank 1 and tank 4 and the flows are indicated by rotameter 1 and 4. Similarly, pump 2 splits its discharge between tank 2 and tank 3 and the split flows are indicated by rotameter 2 and 3. Split flows from pump 1 and pump 2 can be varied by manual adjustment of valves. Tank 1 and tank 2 also receive gravity flow from tank 3 and tank 4, respectively.

Mass balances and Bernoulli's law yield the following nonlinear equations. [1]

$$\frac{dh_1}{dt} = -\frac{a_1}{A_1}\sqrt{2gh_1} + \frac{a_3}{A_3}\sqrt{2gh_3} + \frac{\gamma_1 k_1}{A_1}v_1$$

$$\frac{dh_2}{dt} = -\frac{a_2}{A_2}\sqrt{2gh_2} + \frac{a_4}{A_4}\sqrt{2gh_4} + \frac{\gamma_2 k_2}{A_2}v_2$$

$$\frac{dh_3}{dt} = -\frac{a_3}{A_3}\sqrt{2gh_3} + \frac{(1-\gamma_2)k_2}{A_3}v_2$$

$$\frac{dh_4}{dt} = -\frac{a_4}{A_4}\sqrt{2gh_4} + \frac{(1-\gamma_1)k_1}{A_4}v_1$$

where,

- A_i Cross-section of Tank i (m^2)
- a_i Cross-section of the outlet hole (m^2)
- h_i Water level (cm)
- g Acceleration due to gravity (9.81 m/s^2)

The voltage applied to pump i is v_i and the corresponding flow is $k_i u_i$. The parameters γ_1, γ_2 □ [0,1] are determined from how the valves are set prior to an experiment. The flow to Tank 1 is $\gamma_1 k_1 v_1$ and the flow to Tank 4 $(1-\gamma_1)k_1 v_1$ is and similarly for Tank 2 and Tank 3. The measured level signals are $k_c h_1$ and $k_c h_2$.

The linearized state space equation is given by

$$\frac{dx}{dt} = \begin{bmatrix} \frac{-1}{T_1} & 0 & \frac{a_3}{a_1 T_3} & 0 \\ 0 & \frac{-1}{T_2} & 0 & \frac{a_4}{a_2 T_4} \\ 0 & 0 & \frac{-1}{T_3} & 0 \\ 0 & 0 & 0 & \frac{-1}{T_4} \end{bmatrix} x + \begin{bmatrix} \frac{\gamma_1 k_1}{A_1} & 0 \\ 0 & \frac{\gamma_2 k_2}{A_2} \\ 0 & \frac{(1-\gamma_2)k_2}{A_3} \\ \frac{(1-\gamma_1)k_1}{A_4} & 0 \end{bmatrix} u$$

$$y = \begin{bmatrix} k_c & 0 & 0 & 0 \\ 0 & k_c & 0 & 0 \end{bmatrix} x$$

Where, the time constants are

$$T_i = \frac{A_i}{a_i}\sqrt{\frac{2h_i^0}{g}}, \quad i=1, 2, 3, 4$$

The corresponding transfer function matrix is

$$G(s) = \begin{bmatrix} \frac{\gamma_1 c_1}{1+sT_1} & \frac{(1-\gamma_2)c_1}{(1+sT_3)(1+sT_1)} \\ \frac{(1-\gamma_1)c_2}{(1+sT_4)(1+sT_2)} & \frac{\gamma_2 c_2}{1+sT_2} \end{bmatrix}$$

Where,

$$c_1 = \frac{T_1 k_1 k_c}{A_1} \text{ and } c_2 = \frac{T_2 k_2 k_c}{A_2}$$

The linearized dynamics of the process exhibits a multivariable zero that can be moved from one side of the complex plane to the other one by changing the valves positions. System is in minimum phase when $\gamma_1 + \gamma_2$ is between 1 and 2. System is in non minimum phase when the sum is less than 1. This process is found to be ideally suited to illustrate many concepts in multivariable control.

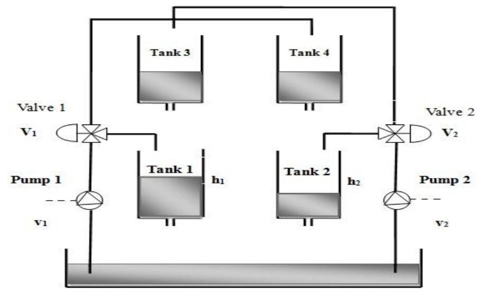

Fig. 1 Schematic diagram of the Quadruple-Tank Process

Fig. 2 Laboratory setup of Quadruple Tank Process

III. DECENTRALIZED PI CONTROLLER

The decentralized control law will be of the form u=diag $\{C_1, C_2\}$ (r-y) as given in the Fig.3. [5]

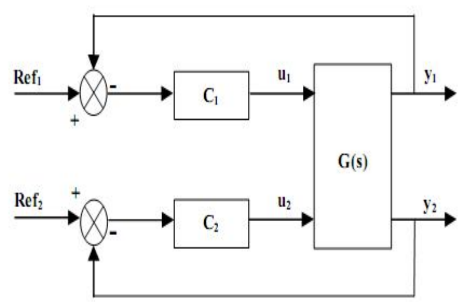

Fig. 3 Decentralized PI Structure

PI controllers are of the form

$$C_l(s) = k_{pl} + \left(\frac{K_{il}}{s}\right) \quad ; l=1, 2$$

are tuned using the formula

$$\left.\begin{aligned} K_l &= \frac{T_{il}}{K_p T_c} \\ T_c &= 0.5 T_{il} \end{aligned}\right\} ; l=1, 2$$

IV. TYPE-1 FUZZY LOGIC CONTROLLER

In general, Type-1 Fuzzy logic uses simple rules to describe the system of interest, rather than the analytical equations, making it easy to implement. An advantage, such as robustness and speed, fuzzy logic is one of the best solutions for non-linear system modeling and control. Type-1 Fuzzy logic controller has four main components. They are fuzzifier, knowledge base, inference mechanism and defuzzifier. Fuzzifier converts the crisp input signal into fuzzified signals identified by membership functions into fuzzy sets. The knowledge base consists of rule base and data base. The inference mechanism evaluates which control rules are relevant at the current time and then decides what the input to the plant should be. Finally the defuzzification process converts the fuzzy output into crisp controlling signal. The block structure of T1FLC is shown in Fig.4 below.

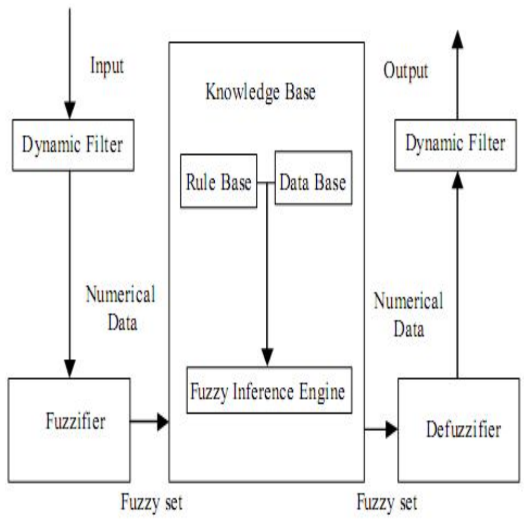

Fig. 4 Block Structure of T1FLC

The control inputs, error (e) and change in error (ce) for Type-1 FLC and its membership function is shown in Fig. 5 below.

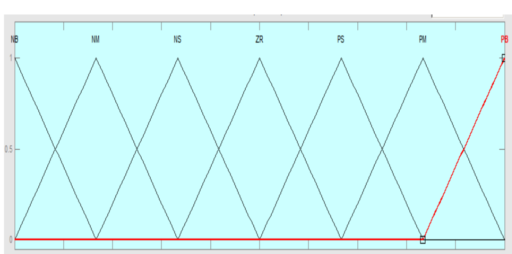

Fig. 5 Membership Function for T1FLC inputs e and ce

The fuzzy surface for error, change of error and output of the system is generated in MATLAB. And the fuzzy surface seems to have more roughness that is shown below in Fig. 6 for T1FLC.

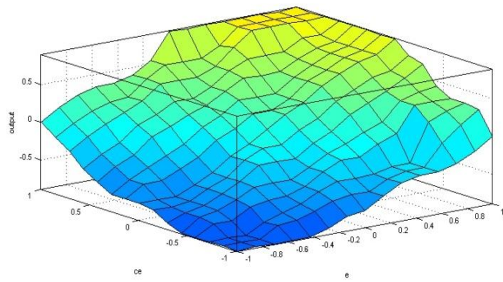

Fig. 6 Fuzzy Surface for T1FLC

V. INTERVAL TYPE-2 FUZZY LOGIC CONTROLLER

Type-1 Fuzzy Logic Controllers (FLCs) have been applied to date with great success to many different applications. However, for dynamic unstructured environments and many real-world applications, there is a need to cope with large amount of uncertainties. The traditional type-1 FLC using crisp type-1 fuzzy sets cannot directly handle such uncertainties. A type-2 FLC using type-2 fuzzy sets can handle such uncertainties to produce a better performance. Hence, type-2 FLCs will have the potential to overcome the limitations of type-1 FLCs and produce a new generation of fuzzy controllers with improved performance for many applications, which require handling high levels of uncertainty. The block structure of IT2FLC is shown in Fig.7 below.

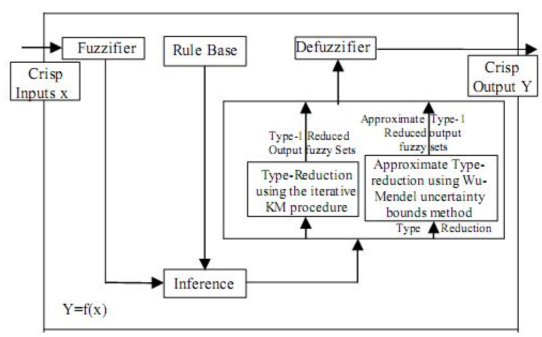

Fig. 7 Block Structure of IT2FLC

The control inputs, error (e) and change in error (ce) for Interval Type-2 FLC and its membership function is shown in Fig. 8 below.

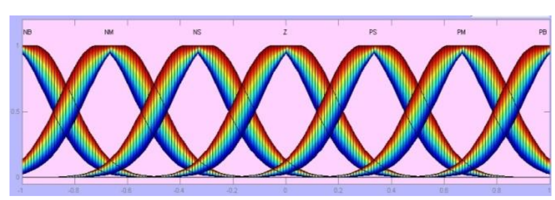

Fig. 8 Membership Function for IT2FLC inputs e and ce

From the defined rules, using the error, change of error and output the fuzzy surface is generated in MATLAB. The fuzzy surface for IT2FLC which is comparatively smoother than T1FLC is shown below in Fig. 9 for IT2FLC.

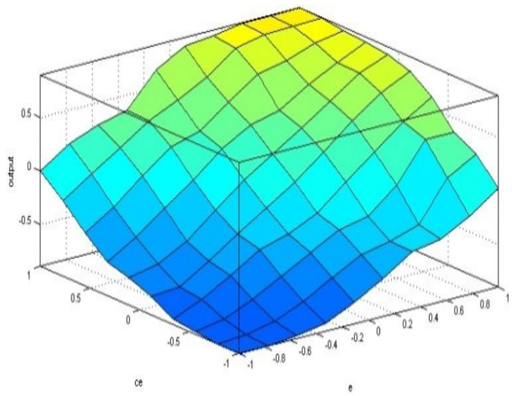

Fig. 9 Fuzzy Surface for IT2FLC

Vertices and the bases of the membership functions are tuned for a given system to get required response. Once the membership functions are created the next step is the formation of rules between input and output membership functions. Fuzzy rules are as shown in Table I.

TABLE I
RULE BASE FOR T1FLC & IT2FLC

ce / e	NB	NM	NS	ZR	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	ZR
NM	NB	NB	NM	NS	NS	ZR	PM
NS	NB	NM	NS	NS	ZR	PS	PM
ZR	NM	NM	NS	ZR	PS	PM	PB
PS	NM	NS	ZR	PS	PS	PM	PB
PM	NS	ZR	PS	PS	PM	PB	PB
PB	ZR	PS	PS	PM	PB	PB	PB

VI. SIMULATION RESULTS

Controllers designed in sections III, IV and V are simulated using MATLAB/Simulink. The parameters of the quadruple tank system are shown in Table II. Parameters of the controllers are given in the Table III.

TABLE II.
QUADRUPLE TANK PROCESS PARAMETER VALUES

Parameter	Values
Diameter of Tank	15cm
Diameter of outlet	1.6cm
γ_1	0.6
γ_2	0.6
Max input flow	600 litres/hour

TABLE III.
CONTROLLER PARAMETERS

Type of Controller	Controller Parameters
Decentralized PI	K_{p1} = 5.248 K_{p2} = 5.084 K_{i1} = 0.1253 K_{i2} = 0.0913

System response for heights h_1 and h_2 of QTP, for the set point of 23.5cm and 27.5cm are shown in Fig.10 and 11 respectively.

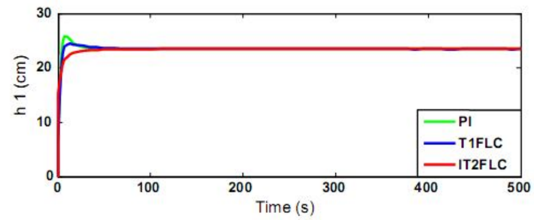

Fig. 10 System response for level h_1

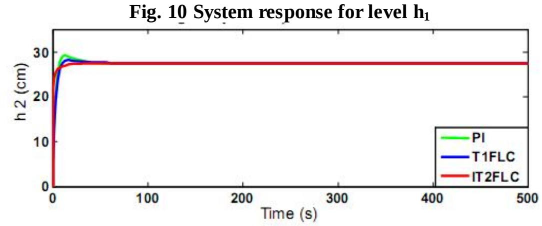

Fig. 11 System response for level h_2

The servo response for the level h_1 for two different step changes i.e. a negative step change of 35% at 2000 second and a positive step change of 50% at 4000 second are shown in Fig. 12. Similarly the servo response for the level h_2 for two different step changes i.e. a negative step change of 45% at 2000 second and a positive step change of 60% at 4000 second are shown in Fig. 13.

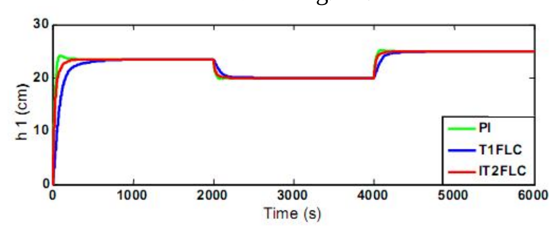

Fig. 12 Servo response for level h_1

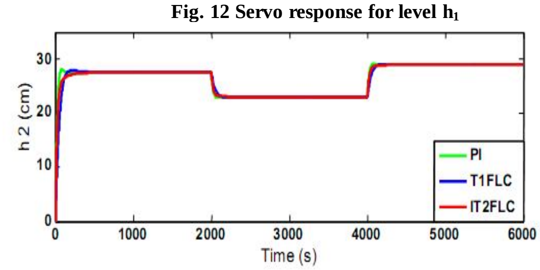

Fig. 13 Servo response for level h_2

The regulatory response of the QTP for the process variables (i.e. level h_1 and h_2) are shown in the Fig. 14 and 15 After reaching a steady state, an input disturbance of 33% i.e. 200 litres/hour, is given at 600 second.

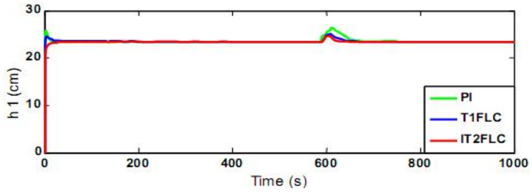

Fig. 14 Regulatory response for level h_1

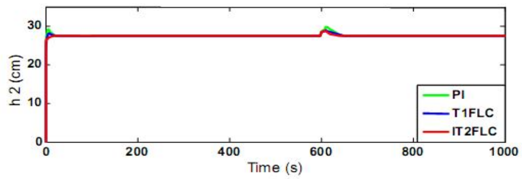

Fig. 15 Regulatory response for level h_2

Comparison of performances of decentralized PI, T1FLC and IT2FLC are given in Table IV, V and VI respectively. It can be observed that IT2FLC has less settling time and over/undershoot in all the three responses. But in servo response the IAE is very less in T1FLC.

TABLE IV.
COMPARISON OF STEP RESPONSE OF DECENTRALIZED PI, T1FLC & IT2FLC

Type of Control	**Settling Time (s)**		**Peak Overshoot (%)**		**IAE**	
	h_1	**h_2**	**h_1**	**h_2**	**h_1**	**h_2**
Decentralized PI	110	92	9.78	3.87	128.19	149.76
T1FLC	100.2	78	4.25	2.54	126.6	145.8
IT2FLC	80.3	60	0	0	82.9	73.7

TABLE V.
COMPARISON OF SERVO RESPONSE OF DECENTRALIZED PI, T1FLC & IT2FLC

Step Change (cm)	**Type of Control**	**Settling Time (s)**		**Overshoot / Undershoot %**		**IAE**	
		h_1	**h_2**	**h_1**	**h_2**	**h_1**	**h_2**
(For h_1 23.5-20) (For h_2 27.5-23)	PI	380	320	1.01	0.86	474.8	150.2
	T1FLC	578	450	0	0.43	475.49	163.40
	IT2FLC	255	300	0	0	474.89	149.89
(For h_1 20-25) (For h_2 23-29)	PI	360	345	0.8	0.68	189.37	220.98
	TIFLC	620	590	0	0.34	192.19	221.87
	IT2FLC	210	240	0	0	191.60	221.28

TABLE VI.
COMPARISON OF REGULATORY RESPONSE OF DECENTRALIZED PI, T1FLC & IT2FLC

Controller	**Settling Time (s)**		**Overshoot (%)**		**IAE**	
	h_1	**h_2**	**h_1**	**h_2**	**h_1**	**h_2**
PI	103	98	5.6	5.1	128.3	149.9
T1FLC	69	54	4.2	3.9	122.4	140.4
IT2FLC	43	33	2.1	1.7	123.0	142

VII. CONCLUSION

Interval Type-2 Fuzzy Logic and Type-1 Fuzzy Logic Controllers are designed to control the level of the quadruple tank process. The IT2FLC results are compared with T1FLC and decentralized PI controllers. The settling time of tank 1 for T1FLC is 100.2 sec and IT2FLC is 80.3 sec and tank 2 for T1FLC is 78 sec and IT2FLC is 60 sec. The Integral Absolute Error for tank 1 for T1FLC is 126.6 and for IT2FLC is 82.9. From servo response it can be observed the system settles faster with IT2FLC than conventional T1FLC for a given set of controller parameters, but the IAE is higher than IT2FLC. From the regulatory responses it can be found that disturbance rejection is faster with IT2FLC than conventional T1FLC and decentralized PI controller.

REFERENCES

[1] K.H.Johansson, "The Quadruple Tank Process – A Multivariable Laboratory Process with an adjustable zero", IEEE Transactions on Control Systems Technology, Vol. 8, No.3, May 2000, pp. 456-465.

[2] W.L.Luyben (1986), "Simple method for tuning SISO controllers in multivariable systems", Ind. Eng. Chem. Process Des. Dev. pp.654-660.

[3] S.J.Shiu and S.H.Huang, "Sequential design method for multivariable decoupling and multiloop PID controllers", 1998, Industrial & Engineering Chemistry Research, Vol. 37, pp. 107-119.

[4] W.Tan, J.Z. Liu and P. K. S. Tam, "PID tuning based on loop-shaping control". IEEE proceedings on Control Theory and Applications, 1998, 145(4), pp 485-490.

[5] M.Zhuang and D.P Atherton, "PID controller design for a TITO system", IEEE Proceedings on Control Theory and Applications, 1994, 141, pp 111-120.

[6] Jerry M.Mendel,"New results about the centroid of an interval type-2 fuzzy set, including the centroid of a fuzzy granule",Information Sciences,117:360–377, 2007.

[7] Oscar Castillo, "Systematic design of a stable Type-2 Fuzzy logic controller", Journal of Applied Soft Computing, Elsevier, Volume 8 Issue 3, 2008, Pages 1274-1279.

[8] H. Wu and J. Mendel, "Uncertainty bounds and their use in the design of interval type-2 fuzzy logic systems," IEEE Transactions on Fuzzy Systems, vol. 10, pp. 622–639, Oct. 2002.

[9] D. Wu and W. Tan, "Type-2 FLS modeling capability analysis," Proceeding of the 2005 IEEE International Conference on Fuzzy Systems, pp. 242–247, Reno, USA, May 2005.

[10] Hani Hagras, "Type -2 FLCs: a new generation of Fuzzy Controllers", IEEE Computational Intelligence Magazine 2007.

[11] DeepaThangavelusamy and Lakshmi Ponnusamy, "Study and comparison of PI controller tuning techniques using Bacteria Foraging and Bacteria Foraging based Particle Swarm Optimization" International Journal of Electrical Engineering. ISSN 0974-2158 Volume 5, Number 5 (2012), pp. 571-586.

[12] R.Suja Mani Malar and T.Thyagarajan, "Modeling of Quadruple Tank System Using Soft Computing Techniques", European Journal of Scientific Research, Vol. 29 No. 2, pp. 249-264, 2009.