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Design Of Multi Model Controller For Non-Linear Process By Using Gap Metric And Pid Filter Controller

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Abstract— The design of multimodel controller for nonlinear process is done with the model bank determination on the basis of Gap metric. Multi linear model controller is designed based on the local linear models by using direct synthesis method with PID filters. Final controller for non-linear model is designed by implementing fuzzy algorithm for all the local linear controllers. Using the direct synthesis method, a proportional-integral-derivative (PID) controller in series with a lead- lag filter is designed for control of the open-loop linear stable and unstable processes. Set-point weighting is considered for reducing the overshoot. The proposed scheme consists of only one tuning parameter and guidelines are provided for selecting the tuning parameter. Good nominal and robust control performances are achieved with the proposed method.

Keywords — Multimodel controller, Direct synthesis method, Gap metric, Non-linear process, PID filter controllers

I. INTRODUCTION

Open-loop unstable processes in industrial and chemical practice are much more difficult to control than that of the stable processes. Desired closed-loop performance cannot be achieved with the conventional proportional-integral-derivative (PID) controller for any adjustable parameters of the controller. The difficulty increases when the process contains a time delay [5]. The time delay occur frequently in process control problems, because of the distance velocity lags, recycle loops, and composition analysis loops, or in the approximation of higher-order systems with a lower-order system with a time delay and imposes limitations such as additional phase lag, leads to instability at low controller gains. The performance specifications can be achieved for stable systems are difficult to achieve for unstable systems [4]. For unstable systems a small delay in the process leads to either oscillatory responses or even unstable responses. Time delay is the time taken by the input to have an effect on the output. There still exist many unstable processes in the chemical plants, even though most chemical processes are open-loop stable. The most common example is the batch chemical reactor, which has a strong nonlinearity due to the heat generation term in the energy balance.

Many design methods have been proposed in the literature based on direct synthesis method for unstable processes. Many of the existing design methods make use of first order Pade's approximation for time delay to derive the controller parameters. However, there is no literature available to specify which approximation for the time delay term should be used when deriving the controller for unstable time delay processes using direct synthesis method. In this work, an attempt is made by considering different type of approximations like Taylor's first and second order, Pade's first, second and half order for the time delay term and a comparative study has been carried out on various UFOPTD processes and Pade's second order approximations is considered for time delay term in the design of the controller.

In this work emphasis is given to study unstable systems with time delay. In particular, the effect of time delay approximations which decides the controller structure is studied in detail. Isothermal CSTR model is considered as a model for the analysis. The controller is designed using direct synthesis method. Direct synthesis method is a well-known technique for design of controllers and the main advantage of this method is the desired output behavior of the closed loop can be specified as a trajectory model based on the process to design the required form of the controller [7]. Gap metric is used to determine the distance between two selected models should not exceed a prescribed level. Using this technique, Local models are selected and Local Controller is designed using linear design techniques. Fuzzy logic is used to design a global controller.

II. ISOTHERMAL CSTR DESCRIPTION

Isothermal CSTR basically a non-linear model exhibiting multiple steady state solutions. The linearized model around an unstable operating point gives an unstable first order model. Time delay is incorporated for the analysis and designing of controller. Direct synthesis method based controller is designed by using Pade's 2nd order approximation.

An isothermal chemical reactor exhibiting multiple steady state solutions is considered. The mathematical model equation of the reactor is given as [5]

$$\frac{dC}{dt} = \frac{Q}{V}\left(C_f - C\right) - \frac{k_1 C}{(k_2 C + 1)^2} \qquad (1)$$

Where Q is the inlet flow rate and C_f is the inlet concentration. The Values of operating parameters are given as Q=0.03333L/s, V=1 L, K_1=10 L/s, and K_2=10 L/mol. For the nominal value of C_f=3.288 mol/L, the steady state solution of the model equation gives the following two steady states at C=1.7673 and 0.01424 mol/L. There is one unstable steady state at C=1.316 mol/L. Feed concentration is considered as the manipulated variable. A measurement delay of 20 sec is also considered. Linearization of model equation around this operating condition C=1.316 mol/L gives the following unstable transfer function model relating the reactor concentration to feed concentration. [5]

$$\frac{\Delta C(s)}{\Delta C_f(s)} = \frac{3.433e^{-20s}}{103.1s - 1} \qquad (2)$$

Based on this model the controller is designed using direct synthesis method.

III. THEORETICAL DEVELOPMENTS

The closed-loop control structure is shown in Figure 1, where $G_p(s)$ is the process transfer function and $G_c(s)$ is the transfer function of the controller. The typical UFOPTD processes exist in most of the chemical and biological systems can be represented by the following transfer function model.

$$G_p = \frac{K_p e^{-\theta s}}{\tau s - 1} \qquad (3)$$

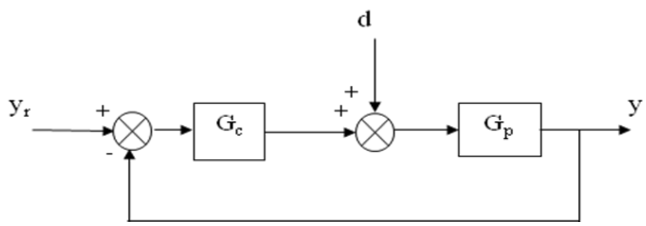

Fig. 1. Feedback control structure

The closed-loop transfer function for the set-point changes is given by

$$\frac{y(s)}{y_r(s)} = \frac{G_c(s)G_p(s)}{1 + G_c(s)G_p(s)} \qquad (4)$$

From Equation (4), using the direct synthesis method, the controller expression is given by

$$G_c(s) = \frac{1}{G_p} \frac{(y/y_r)_d}{[1 - (y/y_r)_d]} \qquad (5)$$

Here, $(y/y_r)_d$ is the desired closed-loop transfer function for a set-point change [7]. The desired closed-loop transfer function should be assumed such that the resulting controller is realizable. With this, the controller is designed for first order unstable process with second order Pade's approximations for the time delay, after specifying the desired closed loop transfer function.

IV. SET POINT WEIGHTING

The PID controller designed based on the direct synthesis method usually introduces a zero in the closed-loop transfer function. This closed loop transfer function zero introduces an overshoot for the servo response (6). The set-point weighting is suggested in the literature to reduce the undesirable overshoot [5]. Hence, in the present work, set-point weighting is considered to reduce the overshoot. With the set-point weighting, the PI controller in (6) is implemented in the form of

$$u(t) = k_c \left[(\varepsilon y_r - y) + \left(\frac{1}{\tau_i} \right) \int e \, dt \right] \qquad (6)$$

Where ε is the set point weighting parameter and its range is $0 < \varepsilon < 1$.The set-point weighting parameter should be selected such that the overshoot of the closed-loop response should give less overshoot and settling time. Based on many simulation studies on different types of UFOPTD processes, ε can be considered as 0.3.

V. SELECTION OF TUNING PARAMETER

It is well-known that there is always a trade off in selecting the desired closed-loop tuning parameter (λ). Fast speed of response and good disturbance rejection are favoured by choosing a small value of λ. However, stability and robustness are favoured by a large value of λ. Hence, the choice of λ is entirely based on the experience of the operator with the control system. Based on many simulation studies, it is observed that the starting value of λ can be considered around the process time delay. If both nominal and robust control performances are achieved with this value, then this value for λ can be taken as the final value. If not, the value should be increased slightly till the nominal and robust control performances are achieved

VI. GAP METRIC

Gap metric is a measure of the distance between two linear systems [1]. It is an extension of α -norm of the difference between two systems. The gap between two linear systems P_1 and P_2 is defined by

$$\delta(P1, P2) = \Pi\zeta(P1) - \Pi\zeta(P2) \qquad (7)$$

Where π denotes the orthogonal projection. It can be applied to integrating and unstable systems because it measures the distance in the closed-loop sense.

In Multi model analysis and controller design for Non-linear processes, a non-linear system is represented as a combination of linear models. Local controllers are designed using linear design techniques. Local models are selected using “gap metric” as a guide line. The idea is that the distance between two selected models should not exceed a prescribed level. Models selected in this method can guarantee the global stability as long as the controller switching is done slowly.

The system exhibits the output multiplicity. Output C is chosen as index variable for its characterizes the nonlinearity and marks the operating region. The operating range Φ is {y/y ∈ [0,9] }

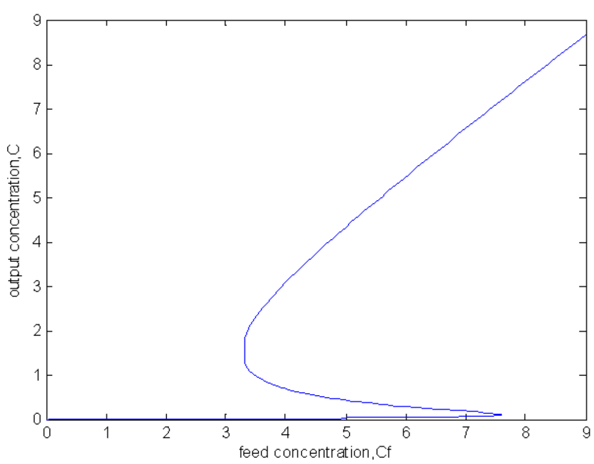

Fig. 2. Steady State Input-Output Map

The gap metric based method is applied to the CSTR system step by step as follows [8] :

Step 1: Distribute N_g=100 linearization points in the entire operating range Φ = {y/y ∈ [0,9]} evenly. Linearize the non-linear system around the 100 points. And 100 tiny models are formulated.

Step 2: Compute the gap metric values between the 100 models. A gap-matrix $[\delta_{ij}]_{100x100}$ is computed. This gap matrix values are shown in figure 3.

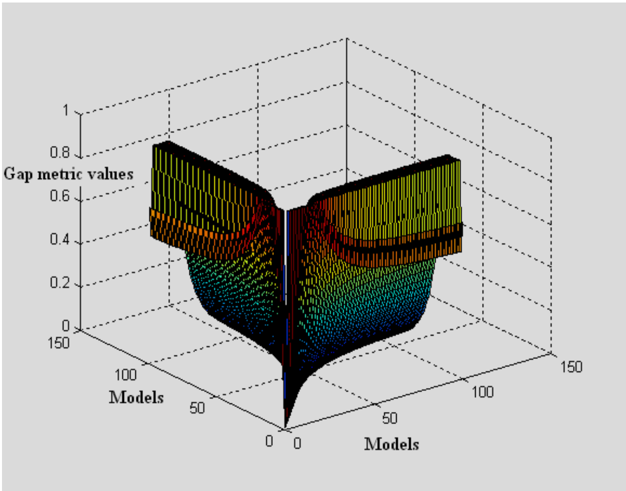

Fig. 3. Gap metric Values

Step 3: Choose δ_g =0.5.

Step 4: Compare δ_{ij} (i ≥ j) with δ_g one by one in sequence from i=j=1.If $\delta_{ij} \geq \delta_g$ stop. Suppose Nk successive tiny models are concerned during comparison, then these tiny models are to be classified in one sub region as shown in the table 1 and 2.

Table 1: Tiny models included with sub region

Sub region	Tiny models included	Sub model
1st	1-2	M(2)
2nd	3-7	M(5)
3rd	8-12	M(10)
4th	13-17	M(15)
5th	18-25	M(22)
6th	26-37	M(32)
7th	38-101	M(64)

Step 5: set i=j=i+1 and repeat step 4 until all tiny models are classified.

Table 2: (7x7) Reduced region of the tiny models included

	1	**2**	**3**	**4**	**5**	**6**	**7**
1	0	1	1	1	0.8819	0.7171	0.6029
2	1	0	0.5873	0.8966	1	1	1
3	1	0.5873	0	0.6478	0.9824	1	1
4	1	0.8966	0.6478	0	0.6254	0.8156	0.8946
5	0.8819	1	0.9824	0.6254	0	0.2761	0.4185
6	0.7171	1	1	0.8156	0.2761	0	0.1522
7	0.6029	1	1	0.8946	0.4185	0.1522	0

Table 3: Tiny models included with further reduced sub region

Sub region	**Tiny models included**	**Sub model**
1^{st}	1-2	M(2)
2^{nd}	3-7	M(5)
3^{rd}	8-12	M(10)
4^{th}	13-17	M(15)
5^{th}	18-101	M(22)

Step 6: Suppose previous steps result in N_m sub models and N_m sub regions. We have to use the same principle to further getting reduced region.

Finally 5 sub models are selected for controller design. The results are given in the table 3 and 4.

The reduced set of models obtained after the gap metric analysis provides enough information to design a multilinear controller that exhibits excellent performance and stability features.

Sub models are found using gap metric method and local controllers are designed.

Table 4: (5x5) Reduced region of the tiny models included

Separate controllers are designed for each sub model and all the controllers are integrated to work in the entire region. Those results are given in following table 5

	1	2	3	4	5
1	0	1	1	1	0.6575
2	1	0	0.5873	0.8966	1
3	1	0.5873	0	0.6478	1
4	1	0.8966	0.6478	0	0.8614
5	0.6575	1	1	0.8614	0

Sub Region	**Controller**
1st region	$7.5008\left(1+\frac{1}{5.58s}\right)$
2nd region	$14.51\left(1+\frac{1}{15.48s}\right)\left(\frac{1+s+0.333s^2}{1+0.204s+0.093s^2}\right)$
3rd region	$13.74\left(1+\frac{1}{6.92s}\right)\left(\frac{1+s+0.333s^2}{1+0.205s+0.088s^2}\right)$
4th region	$13.09\left(1+\frac{1}{6.18s}\right)\left(\frac{1+s+0.333s^2}{1+0.231s+0.0937s^2}\right)$
5th region	$7.5008\left(1+\frac{1}{37.85s}\right)$

Table 5: Controller designed for each Sub model

Finally, the process of integrating the sub controllers is carried out to form a Global controller. The global controller is designed using fuzzy controller.

VII. FUZZY LOGIC CONTROLLER DESIGN

Fuzzy logic is a technique that attempts to systematically and mathematically emulate human reasoning and decision-making. Also allows engineers to exploit their empirical knowledge and heuristics represented in the "if/then" rules and transfer it to a function block. The advantage of fuzzy logic is that it can be easily combined with conventional controllers and substantially enhance their functionality by interpolating the Fuzzy rules between a series of locally linear controllers and schedule gains of a PID controller based on changing operating conditions.

Fuzzification converts each piece of input data to degrees of membership by a lookup in one or several membership functions. The fuzzification block thus matches the input data with the conditions of the rules to determine how well the condition of each rule matches that particular input instance. There is a degree of membership for each linguistic term that applies to that input variable.

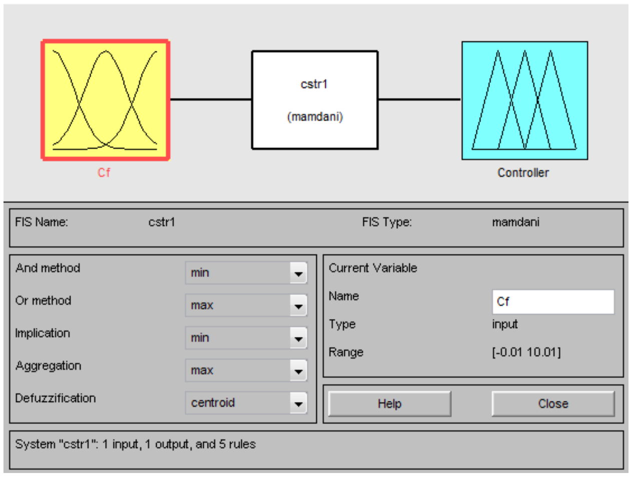

Fig. 4. Fuzzy MATLAB Toolbox

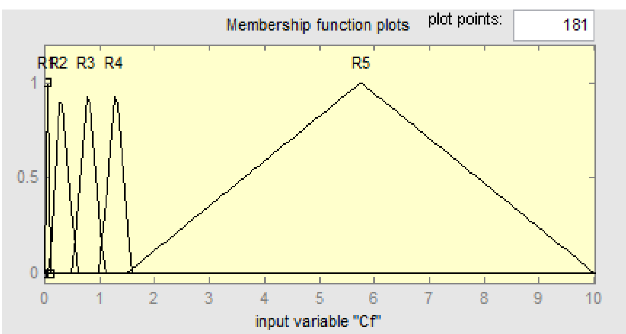

Fig. 5. Membership function for Cf with Linguistic variables

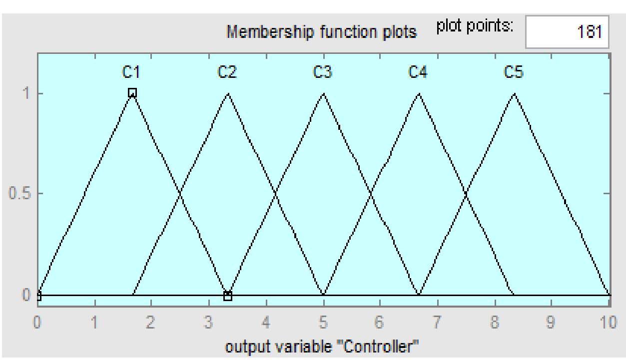

Fig. 6. Membership function for Controller with Linguistic variables

The resulting fuzzy set must be converted to a number that can be sent to the process as a crisp control signal. This operation is called defuzzification. Defuzzification operates on the implied fuzzy sets produced by the inference mechanism and combines their effects to provide the “most certain” controller output (plant input).

VIII. DEFUZZIFICATION

The resulting fuzzy set must be converted to a number that can be sent to the process as a crisp control signal. This operation is called defuzzification. Defuzzification operates on the implied fuzzy sets produced by the inference mechanism and combines their effects to provide the “most certain” controller output (plant input).

IX. RULES FORMATION

The fuzzy system of the proposed control structure contains operator knowledge in the form of IF-THEN rules to decide the gain factors according to the current trend of the controlled process. In the proposed method, the control rules are developed with the error and controller output as a premise and the proportional, integral and derivative gains are consequent of the each rules. The rules are formed using process parameters, controller parameters and Linguistic variables. The fuzzy rule are framed as If (Cf is R1) then (Controller is C1), If (Cf is R2) then (Controller is C2) and so on till Controller C5.

X. SIMULATION RESULTS

The result of Isothermal CSTR was analyzed with different range of Input values. The first analysis is done for the input value 0.1. According to the input range, the input variable ‘Cf’ falls in the region R1. Then the output variable ‘Controller’ is selected based on the rules formed in the Fuzzy controller. If Cf is in region R1 then Controller C1 is selected. The parameters from C1 are used as controller parameters.

The controller parameters obtained for the proposed method with the input variable Cf= 0.1 are tabulated in Table 6.

With these controller settings, the performances of the system is obtained by giving a unit step input at time t = 0 and a negative step disturbance of magnitude 0.5 at t =300 sec respectively. Figure 7 shows the closed loop responses for Isothermal CSTR system when input is in region R1.

Table 6: Parameters from Controller-1

PARAMETERS	NOTATION	VALUE
Fuzzy Output	Y	3.3252
Controller	C1	$7.5008\left(1+\frac{1}{5.58s}\right)$
Proportional Gain	Kc1	9.8268

Integral Time	Ti1	6.5835
Derivative Time	Td1	0.8481

The second analysis is done for the input value 0.5. According to the input range, the input variable 'Cf' falls in the region R2. Then the output variable 'Controller' is selected based on the rules formed in the Fuzzy controller. If Cf is in region R2 then Controller C2 is selected. The parameters from C2 are used as controller parameters.

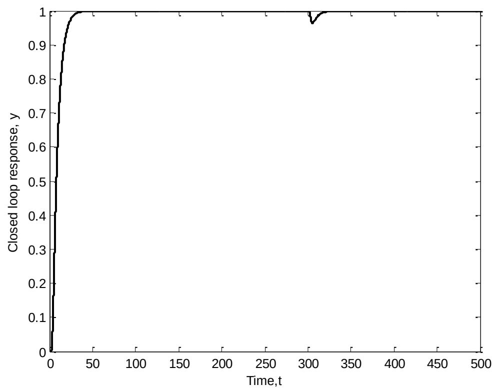

Fig. 7. Closed loop response for CSTR when input is in Region1

The controller parameters obtained for the proposed method with the input variable Cf= 0.5 are tabulated in Table 7.

With these controller settings, the performances of the system is obtained by giving a unit step input at time t = 0 and a negative step disturbance of magnitude 0.5 at t =200 sec respectively. Figure 8 shows the closed loop responses for Isothermal CSTR system when input is in region R2.

Table 7 : Parameters from Controller-2

PARAMETERS	**NOTATION**	**VALUE**
Fuzzy Output	Y	3.4676
Controller	C2	$14.51\left(1+\frac{1}{15.48s}\right)\left(\frac{1+s+0.333s^2}{1+0.204s+0.093s^2}\right)$
Proportional Gain	Kc1	14.5122
Integral Time	Ti1	15.4848

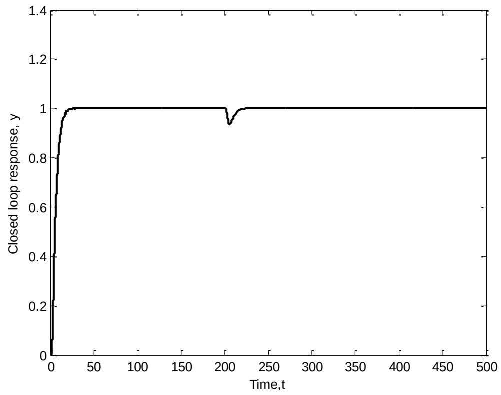

Fig. 8. Closed loop response for CSTR when input is in Region 2

The controller parameters obtained for the proposed method with the input variable Cf= 0.7 are tabulated in Table 8.

Table 8. Parameters from Controller-3

PARAMETERS	NOTATION	VALUE
Fuzzy Output	Y	5.0000
Controller	C3	$13.74\left(1+\frac{1}{6.92s}\right)\left(\frac{1+s+0.333s^2}{1+0.205s+0.088s^2}\right)$
Proportional Gain	Kc1	11.4238
Integral Time	Ti1	9.5229

With these controller settings, the performances of the system is obtained by giving a unit step input at time t = 0 and a negative step disturbance of magnitude 0.5 at t =100 sec respectively. Figure 9 shows the closed loop responses for Isothermal CSTR system when input is in region R3.

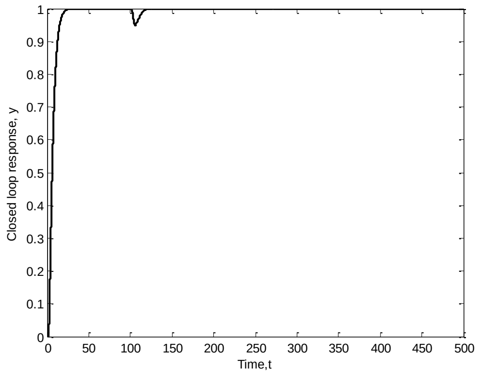

Fig. 9. Closed loop response for CSTR when input is in Region 3

The fourth analysis is done for the input value 1.5. According to the input range, the input variable 'Cf' falls in the region R4. Then the output variable 'Controller' is selected based on the rules formed in the Fuzzy controller. If Cf is in region R4 then Controller C4 is selected. The parameters from C4 are used as controller parameters.

The controller parameters obtained for the proposed method with the input variable Cf= 1.5 are tabulated in Table 9.

Table 9. Parameters from Controller-4

PARAMETERS	**NOTATION**	**VALUE**
Fuzzy Output	Y	6.6746
Controller	C4	$13.09\left(1+\frac{1}{6.18s}\right)\left(\frac{1+s+0.333s^2}{1+0.231s+0.0937s^2}\right)$
Proportional Gain	Kc1	10.6388
Integral Time	Ti1	8.2991

With these controller settings, the performances of the system is obtained by giving a unit step input at time t = 0 and a negative step disturbance of magnitude 0.5 at t =400 sec respectively. Figure 10 shows the closed loop responses for Isothermal CSTR system when input is in region R4.

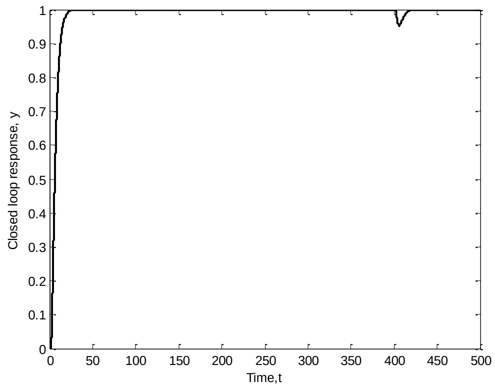

Fig. 10. Closed loop response for CSTR when input is in Region 4

The controller parameters obtained for the proposed method with the input variable Cf= 2.2 are tabulated in Table 10

Table 10 Parameters from Controller-5

PARAMETERS	NOTATION	VALUE
Fuzzy Output	Y	8.3387
Controller	C4	$7.5008\left(1+\frac{1}{37.85s}\right)$
Proportional Gain	Kc1	8.5544
Integral Time	Ti1	38.8501
Derivative Time	Td1	0.9743

With these controller settings, the performances of the system is obtained by giving a unit step input at time t = 0 and a negative step disturbance of magnitude 0.5 at t =350 sec respectively. Figure 11 shows the closed loop responses for Isothermal CSTR system when input is in region R5.

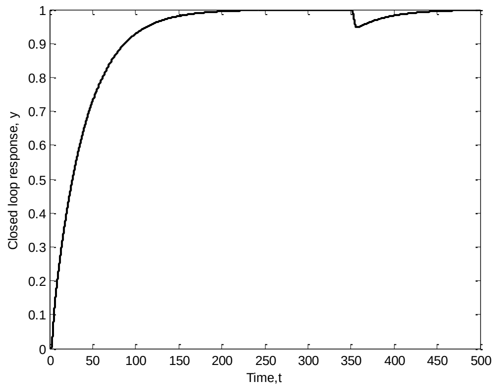

Fig. 11. Closed loop response for CSTR when input is in Region 5

All the designed controllers are tested by varying input ranges. The designed controller was working well in all the ranges.

XI. CONCLUSION

Isothermal CSTR model is considered for the analysis. Using Steady-state input-output response of Isothermal CSTR, the Gap metric values are obtained. Multimodel analysis and controller design for nonlinear processes were done using gapmetric. Then the system is represented as a combination of several local models. Local models are selected using "gap metric" as a guide line. The idea is that the distance between two selected models should not exceed a prescribed level. Models selected in this method can guarantee the global stability as long as the controller switching is done slowly. Local controllers are designed using linear design techniques. Selection of operating point was extended to accommodate performance requirements. Direct synthesis method was used to arrive at the controller structure. The tuning parameter, λ is selected for robust and nominal performances. A global controller is designed using fuzzy controller and then it selects the controller depending upon the input. The controller parameters obtained from the selected controller is used as input for the Isothermal CSTR. The output response is stable. Good nominal and robust control performances are achieved with the proposed method.

The future work is to extend these studies for various integrating systems and to design model predictive control algorithm for non self-regulating processes.

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