Design And Analysis of Intelligent Controller For Temperature Control In CSTR

System

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ABSTRACT-
Continuous Stirred Tank Reactor (CSTR) is one of the most important unit operations in chemical industries which exhibits highly non-linear behaviour and usually has wide operating ranges. Chemical reactions in the reactor are exothermic and require that energy can either be removed or added to the reactor to maintain a constant temperature. In this work, different controllers such as PID, Cascade, IMC controller, Differential Evolution, and Fuzzy Logic Controller have been evaluated. The objective is to control the temperature of CSTR in presence of the set point and analyzed which controller provides the most linear response. Model design and simulation are done in the MATLAB/SIMULINK software. The response of the CSTR, which is observed with applying step input and improved by designing conventional and intelligent controllers.

Keywords- CSTR, Conventional PID, Cascade, IMC, DE Controller and Intelligent FLC and Fuzzy-PID Tuning.

I. INTRODUCTION

The temperature control of continuous stirred tank reactor (CSTR) is basic problem in the process of chemical and polymer industries. The problem of controlling the temperature of CSTR is considered as a challenging issue especially for control engineer corresponding to its non-linear dynamics. In ideal CSTR, it is assumed that the reactor is well mixed meaning that the temperature at different position of the CSTR is identical throughout the reactor. The mixing in the non-ideal CSTR is not uniform, resulting in bypass and dead zone. If heat is evolved due to exothermic reaction, a coolant stream is required to pass through the jacket or coil to remove the extra heat. If endothermic reaction occurs in the system, the flow of heating medium is passing through jacket or coil for maintain the reaction temperature. Any exothermic or endothermic reactions are involved in the reactor, the temperature of the reactions mixture varies with time and the system needs to develop the energy balance equation for this non – isothermal reactor.

Fig.1 Continuous Stirred Tank Reactor

The CSTR is normally run at steady state. The main feature of this type of reactor is the complete uniformity of concentration and temperature throughout the reactor due to the perfect mixing. The CSTR is widely used for large scale production, whereas the batch processing is preferred in case of small – scale operation.
II. MATHEMATICAL MODELING

The examined reactor has real background and graphical diagram of the CSTR reactor shows in Fig.2. The mathematical model of this reactor comes from mass balance, component –A balance and energy balance inside the reactor. Input flow rate $F_i$, concentration of the feed $C_{Ai}$ and temperature $T_f$ are considered. The product steam which is coming out from this CSTR has the flow rate of $F$, concentration in terms of component A is $C_A$ and temperature is $T$. The control objective is to keep the temperature of the reacting mixture $T$, constant at desired value.

Overall mass balance equation -
Rate of mass accumulation = rate of mass input – rate of mass output

$$\frac{dx}{dt} = F_i - F \quad (1)$$

Component A balance equation –
Rate of accumulation of component A = rate of input of component A + rate of generation of component A – rate of output of component A

$$\frac{dC_A}{dt} = \frac{F_i}{v} (C_{Ai} - C_A) - K_0C_A \exp\left(-\frac{E}{RT}\right) \quad (2)$$

Energy balance equation –
Rate of energy accumulation = rate of energy input – rate of energy output – rate of energy removed by coolant + rate of energy added by exothermic reaction

$$\frac{dT}{dt} = \frac{F_i}{v} (T_i - T) - \frac{U_A}{\rho Cp} (T - T_j) + \frac{(-\Delta H)}{\rho Cp} \left(K_0C_A \exp\left(-\frac{E}{RT}\right)\right) \quad (3)$$

From the above equation, (1), (2), and (3), it has been known that CSTR system is considered in steady state form. So, the steady state solution is obtained when

$$\frac{dC_A}{dt} = 0 \quad and \quad \frac{dT}{dt} = 0 \quad \text{That is}$$

$$f_1(C_A, T) = \frac{dC_A}{dt} = 0 = \frac{F_i}{v} (C_{Ai} - C_A) - K_0C_A \exp\left(-\frac{E}{RT}\right) \quad (4)$$

$$f_2(C_A, T) = \frac{dT}{dt} = 0 = \frac{F_i}{v} (T_i - T) - \frac{U_A}{\rho Cp} (T - T_j) + \frac{(-\Delta H)}{\rho Cp} \left(K_0C_A \exp\left(-\frac{E}{RT}\right)\right) \quad (5)$$

To solve these two equations, all parameters are variable except for two ($C_A$, $T$) must be specified.

<table>
<thead>
<tr>
<th>Table 1 Reactor Parameter’s value</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.N</td>
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<tr>
<td>-----</td>
</tr>
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<td>1</td>
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<td>10</td>
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<tr>
<td>11</td>
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</tbody>
</table>

Problem Formulation

The stability of the non-linear equation can be determined by finding the following state space form

$$X' = Ax + Bu \quad (6)$$

$$Y' = Cx + Du$$

Where, the state, inputs and output are in deviation variable

$$A = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix} = \begin{pmatrix} \frac{df_1}{dx_1} & \frac{df_1}{dx_2} \\ \frac{df_2}{dx_1} & \frac{df_2}{dx_2} \end{pmatrix}$$

$$B = \begin{pmatrix} B_{11} \\ B_{21} \end{pmatrix} = \begin{pmatrix} \frac{df_1}{du_1} & \frac{df_1}{du_2} \\ \frac{df_2}{du_1} & \frac{df_2}{du_2} \end{pmatrix}$$

$$C = \begin{pmatrix} 0 & 1 \end{pmatrix}$$

$$D = [0]$$

Using all reactor parameter’s value, the state space model system becomes
The plant transfer function is

\[ T(s) = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \begin{bmatrix} s^2+3.434s+3.5463 \\ s^2+3.434s+3.5463 \end{bmatrix} \begin{bmatrix} 1.4582s+11.652 \\ 1.4582s+11.652 \end{bmatrix} \]

\[ = \begin{bmatrix} \frac{1.4582s+11.652}{s^2+3.434s+3.5463} \end{bmatrix} \]

(7)

III. CONVENTIONAL AND INTELLIGENT CONTROLLER DESIGN

1 PID Controller: - the PID mode is the most popular feedback controller algorithm used in industries. It is a robust, easily understood algorithm that can provide excellent control. The governing equation of PID controller is

\[ y(t) = K_p \left( e(t) + \int_0^t e(\tau)d\tau + T_d \frac{de(t)}{dt} \right) \]

(8)

2 Tuning of PID Controller- Ziegler and Nichols proposed rules for determining values of \( K_p, T_i \) and \( T_d \) based on the transient response characteristics of a given plant. Closed loop oscillation based PID tuning method is a popular method of tuning PID controller. Table 2 Closed loop oscillation based tuning methods

<table>
<thead>
<tr>
<th>Type of Controller</th>
<th>( K_p )</th>
<th>( T_i )</th>
<th>( T_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>0.5K_u</td>
<td>( \infty )</td>
<td>0</td>
</tr>
<tr>
<td>PI</td>
<td>0.45K_u</td>
<td>0.83T_u</td>
<td>0</td>
</tr>
<tr>
<td>PID</td>
<td>0.6K_u</td>
<td>0.5T_u</td>
<td>0.125T_u</td>
</tr>
</tbody>
</table>

3 Cascade Controller- In cascade control configuration, the system has one manipulated variable and more than one measurement. The basic principle of cascade control is that if the secondary variable responds to the disturbance sooner than the primary variable, then there is possibility to capture and nullify the effect of the disturbance before it propagates into the primary variable. Cascade control generally provides better control of the outer loop variable than is accomplished through a single variable system.

4 IMC Controller- Internal model principle states that control can be achieved only if the control system encapsulates, either implicitly or explicitly. The IMC design procedure is exactly the same as the open loop control design procedure. Unlike open loop control, the IMC structure compensates for disturbances in model uncertainties. The IMC tuning (filter) factor “\( \tau \)” is used to detune for model uncertainty. IMC has been divided transfer function of plant into two parts. It has been implemented with CSTR transfer function.

\[ G_p(s) = G_p^+(s)G_p^-(s) \]

Where, \( G_p^+(s) \) is non-invertible portion. 
\( G_p^-(s) \) is invertible portion.

\[ \therefore G_p^+(s) = 1 \]

and \( G_p^-(s) = \frac{1.4582s+11.652}{s^2+3.434s+3.5463} \)

Since, both roots lie in the left side. Thus it is considered that non–invertible portion equal to one. The ideal IMC controller is

\[ Q_C(s) = \left[ G_p^+(s) \right]^{-1} = \frac{s^2+3.434s+3.5463}{1.4582s+11.652} \]

The low pass filter is

\[ f(s) = \frac{1}{(1+0.25s)^2} \]

Thus, a controller can be physically implemented if it is proper. So to make the controller proper, mathematically it is given as

\[ Q_C(s) = f(s) \left[ G_p^-(s) \right]^{-1} = \frac{s^2+3.434s+3.5463}{1.4582s+11.652} \]

(9)

5 Differential Evolution – The differential evolution is used to tune the PID controller parameters for each linear operating region of the CSTR. The PID parameters assigned is used to compute the controller output with error information.

6 Fuzzy Logic Controller- Fuzzy Logic concepts were put forward by Lofti. A. Zadeh, a professor at the University of California at Berkley. Fuzzy Logic is a multi-value logic that allows intermediate values to be defined between conventional evaluations like true/false, yes/no, high/low etc. It is mainly used when human like reasoning and execution needs to be done, to take proper control actions by the controllers. Fuzzy systems suit for the processes in which physical modeling in difficult to arrive at. Also in cases where there is an inadequacy of information for determining the further control actions to be taken.
Thus, the fuzzy logic system has made it easy for its implementation. Fig.3 shows block diagram of FCS.

**Fig.3 Example for Fuzzy Control System**

**Fuzzy Rule Development -**

The Fuzzy Logic control action involves fuzzification, fuzzy inference and de-fuzzification. But the most important factor is the rule set. They define the accuracy with which the control actions will take place. There can be as many number rule sets as possible. In this paper we try to implement the controller action with a smaller rule set. The main input of the Fuzzy controller includes the error and the derivative error. Fig.4 shows fuzzy block being defined using the FIS editor.

**Fig.4 FIS editor for fuzzy block**

**Fig. 5 the FIS editor**

The five MFs are defined depending on the range in which the controller has to be function. Using the fuzzy logic tool box in the Matlab Simulink the required parameters are defined for the membership functions. Fig. 5 shows the membership functions defined using the FIS editor. Fig. 6 and fig.7 show the rule view and Surface view respectively. These rules are classified by AND gate. The range of five MFs is [-10, 10].

**Table 3 Fuzzy Rule Set**

<table>
<thead>
<tr>
<th>E CE</th>
<th>NB</th>
<th>NM</th>
<th>Z</th>
<th>PM</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NM</td>
<td>Z</td>
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<tr>
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<td>Z</td>
<td>PM</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
</tr>
</tbody>
</table>

**IV. MATLAB SIMULATION AND RESULTS**

The fuzzy rule set and the values are defined as

- NB- Negative Big,
- NM- Negative Medium,
- Z- Zero,
- PM- Positive Medium,
- PB- Positive Big

**Fig.8 Matlab Simulink of CSTR with PID controller**
Fig. 9 Output response of CSTR with PID Controller

Fig. 10 Matlab Simulink of CSTR with PID ZN Tuning

Fig. 11 Output Response of CSTR with PID ZN Tuning

Fig. 12 Matlab Simulink of CSTR with Cascade Controller

Fig. 13 Output response of CSTR with Cascade Controller

Fig. 14 Matlab Simulink of CSTR with IMC controller

Fig. 15 Output response of CSTR with IMC controller

Fig. 16 Matlab Simulink of CSTR with DE Controller

Fig. 17 Output response of CSTR with DE Controller

Fig. 18 Matlab Simulink of CSTR with FLC
Table 4 Results analysis of conventional and intelligent controllers

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Controller</th>
<th>Rise Time(Sec.)</th>
<th>Settling Time(Sec.)</th>
<th>Maximum Overshoot (%$M_p$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PID</td>
<td>0.1</td>
<td>3</td>
<td>22.5</td>
</tr>
<tr>
<td>2</td>
<td>PID -ZN</td>
<td>0.1</td>
<td>4.2</td>
<td>49</td>
</tr>
<tr>
<td>3</td>
<td>Cascade</td>
<td>0.47</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>IMC</td>
<td>1.3</td>
<td>2.8</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>DE</td>
<td>0.5</td>
<td>3.1</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>FLC</td>
<td>1.8</td>
<td>3.2</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>Fuzzy-PID Tuning</td>
<td>1.3</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

V. RESULTS AND DISCUSSION

During the comparison of controllers through simulated and real time output, the better performance of Fuzzy – PID tuning controller in the CSTR system has been noticed to achieve precious temperature control and the same can be clearly observed from the real time results of PID, Cascade, IMC, DE and Fuzzy Logic Controller. A Zeigler – Nichols tuning rule of PID control in the CSTR system has also examined (Refer Fig.11) from that it has been observed there is one higher overshoot (49%). During the results comparison and analysis of these results it has been observed that Fuzzy –PID tuning and conventional IMC controller are performed better (Refer Fig.22) than all other controllers examined in this work.

VI. CONCLUSION

In this work, it has been observed that the CSTR is highly non – linear system. Matlab - Simulink of CSTR with conventional and intelligent controllers have been performed. When conventional PID, PID- ZN tuning, cascade, and DE controller are implemented to process with CSTR, the problem of inverse response and steady state error are controlled in the above processes, but then showing instability in terms of rise time, overshoot and settling time. Except IMC controller is defined, resulting in a response with no overshoot and less settling time. In this work, intelligent controller such as Fuzzy Logic and Fuzzy – PID tuning have been performed with CSTR. During the results comparison and analysis
of these results it has been observed that Fuzzy – PID tuning and conventional IMC controller are performed better (Refer Fig.5.22) than conventional and intelligent controllers respectively. But, the settling time of Fuzzy –PID tuning is less than IMC controller. Thus, it has been observed that Fuzzy – PID tuning is the best controller for temperature control in the CSTR system examined in this work.

VII. FUTURE WORK
The temperature control of CSTR can be carried out using techniques such as Artificial Neural Network, Neuro Fuzzy techniques, and Genetic Algorithm.

REFERENCES
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