Performance Analysis of Intelligent Controller for Temperature of Heat Exchanger

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Abstract— Heat exchanger system is generally used in chemical plants as it can sustain wide range of temperature and pressure. Actual purpose of a heat exchanger system is to transfer heat from a hot fluid to a cooler fluid, so temperature control of outlet fluid is of primary concern. Controlling the temperature of outlet fluid of the heat exchanger system by a conventional PID controller can be done. For better disturbance rejection and more optimal control a feed forward controller has been employed. There are many inherent disadvantages of PID controller. Therefore, Internal Model Controller, Fuzzy Logic Controller & Adaptive Neuro-Fuzzy Inference System Controller has been employed to control the temperature of outlet fluid of the heat exchanger. Unit step response analysis has been carried out by using controllers. Result has been tabulated for different controller for the same heat exchanger. It has been observed that fuzzy logic controller provides a satisfactory performance.

Keywords- Fuzzy Logic Controller, Adaptive Neuro-fuzzy Inference System Controller, Internal Model Controller, PID Controller, Heat Exchanger

I. INTRODUCTION

Heat Exchanger is commonly used in a chemical process to transfer heat from the hot fluid to cooler fluid. Different types of heat exchanger are used in industry. But most of the industry uses shell and tube heat exchanger [5][6].

In the present work performance analysis of different conventional and intelligent controller has been studied for a typical heat exchanger. The aim of the proposed controller is to regulate the temperature of the outgoing fluid of a shell and tube heat exchanger to a desired value. Unit step response has been observed for different controllers. It has been observed that fuzzy logic controller provides a satisfactory performance and overcomes the drawbacks of conventional controller.

II. DESCRIPTION OF HEAT EXCHANGER

Typical interacting chemical process for heating consists of a chemical reactor and a ‘shell and tube’ heat exchanger. The super-heated steam comes from the boiler and flows through the tubes. Whereas, the process fluid flows through the shells of the ‘shell and tube’ heat exchanger. The output of the chemical reactor, i.e., process fluid is stored in the storage tank. The storage tank supplies the fluid to the heat exchanger. The heat exchanger heats up the fluid to a desired set point using super-heated steam supplied from the boiler. The storage tank supplies the process fluid to a heat exchanger using a pump and a non returning valve. The super –heated steam comes from the boiler and flows through the tubes, whereas, the process fluid flows through the shells of the shell and tube heat exchanger.

Different assumptions have been considered in present work. The first assumption is that the inflow and the outflow rate of fluid are same; therefore fluid level is maintained constant in the heat exchanger and the second is the heat storage capacity of the insulating wall is negligible. There are two types of disturbances in this process, one is the flow variation of input fluid (dominant) and the second is the temperature variation of input fluid.

The sensing element, ‘thermocouple’ is implemented in the feedback path of the control architecture. The temperature of the outgoing fluid is measured by the thermocouple and the output of the thermocouple is sent to the transmitter unit, which eventually converts the thermocouple output to a standardized signal in the range of 4-20mA. Output of the transmitter unit is given to the controller unit. The controller implements the control algorithm, compares the output with the set point and then gives necessary command to the final control element via the actuator unit. The actuator unit is a current to pressure converter and the final control unit is an...
air to open valve. The actuator unit takes the controller output in the range of 4-20mA and converts it in to a standardized pressure signal in the range of 3-15 psig. The valve actuates according to the controller decisions. Fig.1 shows the feedback control scheme adopted in heat exchanger [3][15].

III. EXPERIMENTAL DATA USED FOR MODELING

Here the heat exchanger system, actuator, valve, sensor are mathematically modeled using the available experimental data. The experimental process data is summarized below [4].

- Exchanger response to the steam flow gain = 50°C/kg/sec
- Time constant of controller valve = 3 sec
- Exchanger response to variation of process fluid flow gain = 1°C/kg/SEC
- Exchanger response to variation of process temperature gain = 3°C/°C
- Control valve capacity for steam = 1.6 kg/sec
- The range of temperature sensor = 50°C to 150°C
- Time constant of temperature sensor = 10 sec
- From the experimental data, transfer functions and the gains are obtained as below.

\[
\text{Gain of current to pressure converter} = 0.75
\]

(i) Flow\( \frac{1}{30s+1} \) (dominant)

(ii) Temperature \( \frac{0.16}{10s+1} \)

- Transfer function of process = \( \frac{50e^{-s}}{30s+1} \)
- Gain of valve = 0.13
- Transfer function of valve = \( \frac{0.13}{3s+1} \)
- Gain of current to pressure converter = 0.75
- Transfer function of disturbance variables

Fig. 2 represents the transfer function block diagram of feedback control of shell and tube heat exchanger.

Auxiliary equation is, 
\[
420s^2 + 0.78K_c + 1 = 0
\]

Substituting \( s = j\omega \) gives \( \omega = 0.218 \) and \( T = 28.82 \)

Ideal PID controller in continuous time is given as
\[
Y(t) = K_p e(t) + \frac{1}{T_1} \int e(t) \, dt + T_d \frac{d}{dt} e(t)
\]

Laplace domain representation of ideal PID controller is 
\[
G_c(s) = \frac{Y(s)}{E(s)} = K_p(1 + \frac{1}{T_1s} + T_ds)
\]

Table 1 gives experimental tuning rules based on closed loop oscillation method [1][10][11].

<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>0.5( K_c )</td>
<td>( \infty )</td>
<td>0</td>
</tr>
<tr>
<td>PI</td>
<td>0.45( K_c )</td>
<td>0.83T</td>
<td>0</td>
</tr>
<tr>
<td>PID</td>
<td>0.6( K_c )</td>
<td>0.5T</td>
<td>0.125T</td>
</tr>
</tbody>
</table>

For the PID controller the values of parameters obtained using Ziegler Nichols closed loop oscillation based tuning methods are 
\( K_p = 14.66 \), \( T_i = 14.41 \), \( T_d = 3.60 \). Usually, initial design values of PID controller obtained by all means needs to be adjusted repeatedly through computer simulations until the closed loop system performs or compromises as desired. These adjustments are done in MATLAB simulation.

The disturbance input introduces error in the system performance. In several systems the disturbance can be predicted and its effect can be eliminated with the help of feed forward controller before it can change output of the system.

\[
G_p(s) = \frac{50e^{-s}}{90s^2 + 33s + 1}, \quad G_d(s) = \frac{1}{30s+1}
\]

The transfer function of the feed-forward controller is
\[
G_{cf}(s) = -\frac{G_d(s)}{G_p(s)} + \frac{1}{G_{cf}(s)}
\]

Here, \( l \) is filter parameter. Its range is from 0 to 1.
IV. INTERNAL MODEL CONTROLLER

Internal model controller provides a transparent framework for control system design and tuning. Fig. 4. Shows the Internal model control scheme. The main feature of internal model controller is that the process model is in parallel with the actual process. The main feature of internal model controller is that the process model is in parallel with the actual process.

\[ G_p(s) = \frac{0.75}{3s+1} \times \frac{50e^{-s}}{30s+1} \]  
\[ G_p(s) = \frac{4.875e^{-s}}{90s^2+33s+1} \]  
(7)
(8)
The process model \( G_p(s) \) is factored into two parts, that is invertible part \( Gp_+ (s) \) and non-invertible part \( Gp_- (s) \). The non-invertible part consists of RHP zeros and time delays. This factorization is performed so as to make the resulting internal model controller stable.

\[ Gp(s) = Gp_+(s)Gp_-(s) \]  
\[ G(s) = [Gp_+(s)]^{-1} \]  
\[ G_{IMC}(s) = Qc(s) = Gc(s)Gf(s) \]  
(9)
(10)
(11)
Where \( Gf(s) \) is a low pass function defined as \( Gf(s) = \frac{1}{(1+\lambda s)^n} \)
Where \( \lambda \) is closed loop time constant. A good rule of thumb is to choose \( \lambda \) to be twice fast as open loop response. Hence \( \lambda=10 \) (Open loop time constant= 30)

\[ Gp_+(s) = \frac{4.875}{90s^2+33s+1} \]  
\[ Gp_-(s) = e^{-s} \]  
\[ G_{IMC}(s) = Qc(s) = [Gp_+(s)]^{-1}Gf(s) \]  
\[ Qc(s) = \frac{4.875(1+10s)^n}{90s^2+33s+1} \]  
(12)
(13)
(14)
(15)
Taking 3rd order low pass filter i.e. \( n=3 \) we get the controller for IMC as

\[ Qc = \frac{90s^2+33s+1}{4875s^3+1462.5s^2+1462.5s+4.875} \]  
(16)

V. FUZZY LOGIC CONTROLLER

The design of fuzzy logic controller is attempted in heat exchanger. The sugeno or Takagi-Sgeno-Kang, method of fuzzy inference, introduce in 1985. It is similar to the Mamdani method in many respects. The first two parts of the fuzzy inference process, fuzzifying the inputs and applying the fuzzy operator, are the same. The main difference between Mamdani and Sugeno is that the Sugeno output membership functions are either linear or constant. The fuzzy controller is designed with single input variable and single output variable. Triangular membership functions are used for input variables [7][8][9][16].

VI. ADAPTIVE NEURO-FUZZY INFERENCE SYSTEM

An adaptive neuro-fuzzy inference system (ANFIS) is a kind of artificial neural network that is based on Takagi-Sugeno fuzzy inference system. The technique was developed in the early 1990s. Since it integrates both neural network and fuzzy logic principles, it has potential to capture the benefits of both in a single framework. Its inference systems correspond to a set of fuzzy IF-THEN rules that have learning capability to approximate nonlinear functions. ANFIS is the implementation of fuzzy inference system (FIS) to adaptive networks for developing fuzzy rules with suitable membership functions to have required inputs and outputs [12][13][14]. Generally learning type in adaptive ANFIS is hybrid learning. General structure of the ANFIS is illustrated in Fig. 6.
The structure of the network is composed of a set of units (and connections) arranged into five connected network layers. This structure contains the same components as the FIS, except for the NN block.

Layer 1 is called as the input layer, Layer 2 consists of input variables (input membership functions). Here, triangular MF is used; Layer 3 is called as the rule layer. Each node (each neuron) in this layer performs the pre-condition matching of the fuzzy rules, i.e., they calculate the activation level of each rule, the number of layers being equal to the number of fuzzy rules. Each node of these layers calculates the weights which are normalized; Layer 4 consists of output variables (output membership functions). Here, triangular MF is used. Layer 5 is called as the output layer which sums up all the inputs coming from the layer 4 and transforms the fuzzy classification results into a crisp (binary).

VII. PERFORMANCE ANALYSIS OF THE DIFFERENT CONTROLLER WITH FEEDBACK

Fig. 7. Simulink model of shell and tube heat exchanger with feedback

PID Controller

Fig. 8. Simulink model of shell and tube heat exchanger with feedback

IMC Controller

Fig. 9. Simulink model of shell and tube heat exchanger with feedback

FLC Controller

Fig. 10. Simulink model of shell and tube heat exchanger with feedback

ANFIS Controller

The comparison among the different controller response with feedback is shown in Fig. 11.
VIII. PERFORMANCE ANALYSIS OF THE DIFFERENT CONTROLLER WITH FEEDBACK PLUS FEED FORWARD

Fig. 12. Simulink model of shell and tube heat exchanger with feedback plus feed-forward PID Controller

Fig. 13. Simulink model of shell and tube heat exchanger with feedback plus feed forward IMC Controller

Fig. 14. Simulink model of shell and tube heat exchanger with feedback plus feed forward FLC Controller

The comparison among the different controller response with feedback plus feed forward is shown in Fig. 16.

IX. RESULTS AND DISCUSSIONS

The comparison among the different controller with feedback & feedback plus feed forward in terms of settling time, and % overshoot as shown in table 2

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>CONTROLLERS</th>
<th>Settling time(sec)</th>
<th>% overshoot</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Feedback with PID</td>
<td>95</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>2. Feedback with IMC</td>
<td>109.5</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>3. Feedback with ANFIS</td>
<td>78</td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>4. Feedback with FUZZY</td>
<td>20</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>5. Feedback plus feed forward with PID</td>
<td>106</td>
<td>71.2</td>
<td></td>
</tr>
<tr>
<td>6. Feedback plus feed forward with IMC</td>
<td>103.3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>7. Feedback plus feed forward with ANFIS</td>
<td>83</td>
<td>3.66</td>
<td></td>
</tr>
<tr>
<td>8. Feedback plus feed forward with FUZZY</td>
<td>16</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
The PID controller with feedback shows a peak overshoot of 40%, and settling time= 95sec, IMC shows peak overshoot of 0%, and settling time 109.5sec, ANFIS shows peak overshoot of 6.4% , and settling time= 78sec and FLC shows peak overshoot of 0%, and settling time= 20sec.

The PID controller with feedback plus feed forward shows a peak overshoot of 71.2%, and settling time= 106sec, IMC shows peak overshoot of 0%, and settling time 103.3sec, ANFIS shows peak overshoot of 3.66% , and settling time= 83sec and FLC shows peak overshoot of 0%, and settling time= 16sec. It is clear from the step response analysis that the FLC controller gives better performance than PID,IMC and ANFIS Controllers.

X. CONCLUSION

In the present work, performance analysis of different conventional and intelligent controller has been studied for a typical heat exchanger. The aim of the proposed controller is to regulate the temperature of the outgoing fluid of a shell and tube heat exchanger to a desired value in the shortest possible time with minimum or no overshoot.

Unit step response has been observed for different controllers. It has been observed that fuzzy logic controller provides a satisfactory performance and overcomes the drawbacks of conventional PID controller and internal model based controller (IMC).

Fuzzy logic controller has demonstrated 100% improvement in the overshoot as compared to the conventional PID controller. Fuzzy logic controller has improved the settling time as compared to PID Controller, Internal Model Controller (IMC), and Adaptive Neuro-Fuzzy Inference system (ANFIS). The fuzzy logic controller with feedback plus feed-forward gives better performance.

References