Temperature Control Of Continuous Stirred Tank Reactor Using Model Predictive Controller

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Abstract- The objective of this paper is to develop a Model Predictive Control (MPC) to control the temperature in Continuous Stirred Tank reactor (CSTR), which exhibits highly nonlinear dynamics. PID controllers are widely used in industry, however, the control of nonlinear systems using PID control scheme doesn’t give satisfactory performance at all operating points. The reason behind is that the parameters of these nonlinear processes vary with the operating conditions. Here, a model-based predictive controller is designed and implemented for the temperature control of the process reactor of Continuous Stirred Tank Reactor (CSTR). The MPC Controller and PID controller both are tuned and simulated using MATLAB. The transients results are compared in both PID and MPC controller and analysis is conducted.

Index Terms- Continuous Stirred Tank Reactor (CSTR), MPC, PID, Servo-Regulatory Response.

I. INTRODUCTION

Continuous Stirred Tank Reactor (CSTR) is an important part in the process control industry as well as academia and offering a diverse range of researches in the area of chemical and control engineering. Continuous stirred tank reactor (CSTR) exhibits quite nonlinear dynamic behaviour offering a diverse range of researches in this field. The nonlinearities can be complex and the performance of conventional control techniques under such condition suffers. It is generally difficult to obtain an accurate model because of the inherent complexity of the chemical processes. Model Predictive Control (MPC), approaches have been recognized as the accepted standard to cope with some of the difficult control problems in process industry and is a powerful optimal control algorithm that is able to yield a good performance for nonlinear systems. It is popular since the last few decades in research and implemented in industry as well. The effectiveness of the MPC control scheme is significant to have the satisfactory performance. MPC control scheme uses the linear dynamic model for prediction, limit their applicability to a small range of operation to system exhibiting the nonlinear dynamics. Model predictive control is an increasingly significant and popular control approach because of its use of a possibly nonlinear multivariable process model and its ability to handle constraints on inputs, states and outputs. It uses open loop constrained optimization of finite horizon control criteria in a receding horizon approach. It is generally difficult to obtain an accurate model because of the inherent complexity of the chemical processes. Any advanced process control method mainly considers the explicit prediction of future plant behaviour and computation of appropriate corrective control action required to drive the predicted output as close as possible to the desired target value. But PID, regarded as the standard control scheme to be implemented and applicable for the SISO process and linear systems. However, the presence of the nonlinearity limit their performance.

The efficiency of the proposed MPC scheme has been demonstrated by conducting simulation studies on the Continuous Stirred Tank Reactor (CSTR). This paper illustrates the advantage of MPC over conventional controller by servo-regulatory responses. This paper contributes mainly to demonstrate the development of MPC for Continuous Stirred Tank Reactor (CSTR).

II. SYSTEM IDENTIFICATION

A. Experimental Setup

A real time experimental setup is constructed for CSTR. The process control system is interfacing DAQ module to the user controlling system i.e. personal computer. The laboratory set up for this system is shown in figure I. it consists of a feed tank a cold water reservoir, pumps, rotameter, temperature sensors (RTD), a pneumatic pressure control valve, electro-pneumatic converter (I/P converter) an interfacing DAQ module and a personal computer (PC). Temperature sensors are interfaced with computer using DAQ module in the USB port of the PC. The experimental control algorithm developed on MATLAB SIMULINK on the personal computer and implemented on the system through the DAQ module.

Figure I. Experimental setup for temperature control of CSTR
After computing the control algorithm in the PC, control signal is transmitted to I/P converter in the form of current signal (4-20mA), which passes the air signal to the pneumatic control valve. The pneumatic control valve is actuated by this signal to produce the required flow of water through the cooling jacket.

**B. System Identification**

In order to implement the Model predictive Controller, the model of the system is required and it needs to be derived. The model is found out by empirically determining the system. By keeping the average inlet flow rate constant of the feeding hot water to the reactor, the output temperature of the reactor is continuously monitored. A step change was given in the feeding temperature and again the reactor temperature is measured. This open loop input and output data is recorded, and is used in System Identification Toolbox to find out the model of the system. From this transfer function is obtained, which again exhibits the nonlinear response. The following transfer function is obtained. This transfer function will be further used for the controlling temperature of the reactor using model predictive controller scheme. The transfer function model of the CSTR real process is realized using MATLAB and simulations are performed.

Transfer function of the CSTR:

\[ G(s) = \frac{Y(s)}{U(s)} = \frac{-0.12s + 0.12}{3s^2 + 4s + 1}. \]

Thus the mathematical model of CSTR real process was obtained in the discrete state space form as follows.

\[ A = \begin{bmatrix} -1.3333 & -0.3333 \\ 1 & 0 \end{bmatrix}; \]
\[ B = \begin{bmatrix} 1 \\ 0 \end{bmatrix}; \]
\[ C = \begin{bmatrix} 0.04 \\ 0.04 \end{bmatrix} \text{ and } D = [0 \\ 0]. \]

**III. COMPUTING CONTROL STRATEGIES**

**A. PID Controller**

Traditional PID controllers are easy to understand and implement, and is very popular in linear control systems. However, PID always has this requirement of re-tuning when desirable working condition changed or emergency happens. As implied by the name, a PID (proportional-integral-derivative) controller consists of three parts: proportional part, integral part and derivative part.

The weighted sum of these three parts is used to adjust the process via a control valve. Usually a PID is formulated as follows:

\[ MV(t) = P_{out} + I_{out} + D_{out} \]

where, \( P_{out} = K_p e(t) \)
\[ I_{out} = K_i \int e(t) \, dt \]
\[ D_{out} = K_d \frac{de(t)}{dt} \]

Here \( K_p, K_i \) and \( K_d \) are called proportional gain and derivative gain. They are key parameters of the PID controller. The tuning of the PID controller is performed in MATLAB Simulink.

**B. MPC Controller**

The model predictive control is a strategy that is based on the explicit use of some kind of model of the system which is able to predict the future values of the output over a certain time horizon, the prediction horizon. The control algorithm can be described as follows as follows [3].

1. At each sampling time, the value of the controlled variable \( y(t+k) \) is predicted over the prediction horizon \( k=1,……P \). This prediction depends on the future instant values of the control variable \( u(t+k) \) within control horizon of \( k=1,……M \), where \( M \leq P \).

2. A reference trajectory \( r(t+k) \), \( k=1,……N \) is defined which describes the desired trajectory to be followed as reference over the prediction horizon by the system response.

3. The future control action \( u(t+k) \) is computed such that a cost function is minimised.

4. The optimised control is then applied to the plant and the plant outputs are measured, by using these measurements of the plant states as the initial states of the model to perform the next iteration.

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*Figure 2. Receding Horizon Control*

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*Figure 4. PID control system.*
Step 1 to 4 are to be repeated at each sampling instant; this is called receding horizon strategy. The above steps can be expressed by the following equations:

$$\min \left( \sum_{i=1}^{p} [x_d(k + 1) - x(k + l)]^2 \right)$$

(3)

where $k$ is the time step, $u(k)$ is the control vector at time $k$, ($x$) and $x(k)$ are the desired output (reference) and predicted output vector of the model at time $k$ respectively, $p$ is the prediction horizon time. The block diagram of a model predictive controller is shown in Figure 3.

As the control variables in a MPC controller are calculated based on the predicted output, the model reflects the dynamic behaviour of the system accordingly.

**IV. SIMULATION RESULTS AND ANALYSIS**

This section consists the comparative analysis between conventional control of PID and MPC control through servo and regulatory response of CSTR model in MATLAB. The temperature of the reactor of CSTR plant has been measured using temperature sensor and the opening of the pressure control valve is controlled according to the control action generated as per the control algorithm used. In all the simulation runs, the process is simulated using the transfer function model of the CSTR plant, and is given by equation (1):

$$G(s) = \frac{Y(s)}{U(s)} = \frac{-0.12s+0.12}{3s^2+4s+1}$$

The PID parameters for simulation are tuned itself in the MATLAB, which offers the better response over the manual tuning through any tuning algorithm. The parameters are as follows:

<table>
<thead>
<tr>
<th>P</th>
<th>I</th>
<th>D</th>
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<tbody>
<tr>
<td>13.0160354</td>
<td>2.59398180</td>
<td>3.22592261</td>
</tr>
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</table>

The servo response for the transfer function model of the plant is simulated. The servo tracking ability of the controller is compared. The set point is varied in –

Step 4: From the responses shown in the Figure 4, for the given set point MPC controller has the better servo responses.

The following figure shows the servo-regulatory response of the conventional PID and MPC controller. The PID Controller response is simulated by using the transfer function model of the plant and MPC controller is simulate with the Control Horizon 0.5 (time units), Prediction Horizon 10 (intervals) and Control Horizon 2 intervals. A set point variation is given from 45 degree Celsius to 40 degree Celsius.

Table 1. Time domain response of PID and MPC Controller

<table>
<thead>
<tr>
<th>Time domain Specification</th>
<th>PID</th>
<th>MPC Controller</th>
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<tbody>
<tr>
<td>Settling Time (sec)</td>
<td>15.462</td>
<td>6.112</td>
</tr>
<tr>
<td>Overshoot %</td>
<td>3.125 %</td>
<td>0.562%</td>
</tr>
<tr>
<td>Rise Time (sec)</td>
<td>1.864</td>
<td>3.036</td>
</tr>
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</table>

Table 1 shows the time domain response of the PID and MPC controller. The settling time specification of the time domain response of MPC controller is much better than that of PID. And same with the overshoot. The more the overshoot gives the transients in the response though gives a short rise time, the stability of the system to keep in mind. In these simulation results MPC controller yields the better and stable
response.

CONCLUSION

The CSTR process is highly nonlinear process. The modelling of the CSTR process is identified and implemented, the model is found out by empirically determining the system deriving from the data the real process. The MPC controller and PID controller are implemented to control the temperature inside the reactor. The simulations are implemented to track the servo response and regulatory response. The simulation results proves that the MPC control method is an easy tuning and more effective way to enhance the stability of time domain performance of the temperature of CSTR process. The simulation results demonstrate the capability of the proposed identification strategy to effectively identify the compact and approximate accurate model for the CSTR process. It is shown that the proposed model predictive control design yields better improvement with significant better response time for both servo and regulatory control objectives.

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