Improving the Transient Response Performance of CSTR Using MRAC

EZE P. C.[1], JONATHAN, A. EMMANUEL [2], OKORONKWO, EMMANUEL A.[3], AKIN, M. PHILLIPS [4]

[1] *Department of Electrical and Electronic Engineering Technology, Covenant Polytechnic, Owerrinta, Nigeria*

[2, 3,4] *Department of Electrical and Electronic Engineering, Federal University of Technology, Owerri, Nigeria*

Abstract- This paper has implemented an adaptive control technique for Continuous Stirred Tank Reactor (CSTR) process. The transfer function representing the dynamics of a CSTR process was obtained. The system was modeled in Simulink and simulated without being compensated. The output response in terms of concentration to unit step input revealed that a compensator was needed to improve the transient characteristics performance. A Model Reference Adaptive Controller (MRAC) was designed based on the MIT rule and integrated with CSTR process. The Simulink model of the MRAC control for CSTR process is developed. The performance of the MRAC controller was analyzed in terms of Integral Square Error (ISE), Integral Absolute Error (IAE) and Integral Time Absolute Error (ITAE). The simulation results obtained showed that the controller provided robust and improved tracking error for the range of gain selected, with gain adjusted to 25 providing the most effective and robust tracking error performance with ISE of 0.3324, IAE of 0.4408, and ITAE of 0.3945.

Indexed Terms- Adaptive control, CSTR, MRAC, Controller

I. INTRODUCTION

Continuous Stirred Tank Reactor (CSTR) is used in many chemical plants in the form of single tank or more tanks in series [1]. The study of dynamic characteristics of CSTR has increased the computational efficiency of chemical processes where it is applied. CSTR is an indispensable unit in many chemical plants, and has been frequently used to serve multi-purpose production objective [2].

According to Zhao et al [3], the operation of CSTRs are performed around a certain steady point which is linked to the optimal output or optimal production process to achieve high conversion rate and maximize economic gains. In chemical process control point of view, the dynamics of CSTRs are regarded as highly nonlinear. Some of the notable dynamic characteristics of CSTRs are relatively degree, unmeasured states zero dynamics. The dynamics characteristics make the design of the process algorithm for effective CSTRs very challenging, especially in the presence of the external perturbation and/or system uncertainty [3] [4]. Also, another challenging from the economic point of view, facing process engineers will be the variable cost reduction while keeping product quality [2].

In order to enhance the operation of the CSTR process system, control algorithm has been made an integral part. An automatic controller must be able to enhance the process operation within a given range of operating condition [5]. Many control strategies have been used to felicitate the performance of the CSTR process in industry. Among the control strategies used is the Proportional Integral and Derivative (PID) controller. The PID controller, though the most commonly used in process industries, suffers from the problem of nonlinearity. This has prompted the application of several other techniques to regulate chemical processes such as Fuzzy Logic Controller (FLC), Model predictive Controller (MPC), Adaptive controllers, and hybrid control techniques. These controllers are believe to overcome the problem of nonlinearity in chemical processes better than conventional control technique like Proportional Integral (PI), PID, lead or lag compensators.

Since the traditional PID controller cannot effectively deal with problems that occur in complex nonlinear processes, this paper presents a Model Reference Adaptive Control (MRAC) to control the output response, that is, the concentration of CSTR process. The remaining part of this paper has been divided into four different sections: literature review, system design and configuration, simulation result and discussion, and conclusion.

II. REVIEW OF RELATED LITERATURE

Maheshwari et al [6] studied design and analysis of PID controller for CSTR process. The objective of the study was to control temperature and load disturbance rejection of CSTR. Simulation result showed that the PID controller provided a less percent overshoot with efficient load disturbance rejection with a minimum setting time.

Aboelela et al [7] presented design and implementation of a PID controller for a CSTR system using particle swarm algorithms. It applied proportional integral (PI) and PID controller tuned with PSO, Adaptive Weighted PSO (AWPSO) algorithms to CSTR process to take care of the temperature and concentration control. Three error criteria were used to achieve the optimization process. These include integral of square error (ISE), the Integral of Absolute Error (IAE) and integral of Time Absolute Error (ITAE). In order to test the robustness of temperature and concentration performance of the process, some of the parameters of CSTR were altered. It maintained that better performance algorithm was observed.

Khanduja [8] presented CSTR control by using model reference adaptive control and PSO. A comparative analysis of CSTR control based on model reference adaptive control (MRAC) and optimal turning of PID control based on PSO. The Massachusetts Institute of Technology (MIT) rule and Lyapunov rule were used to develop the adaption law for the MRAC techniques. The PID Controller parameters were turned based on PSO to obtained optimized operating point for minimum ISE condition. The simulation results show that the PID controller turning based on PSO provided better control response of the MRAC.

Jhon et al [9] presented a tuning proposal for direct fuzzy PID controllers oriented to industrial Continuous processes. It presented a simple but effective systematic method for many direct fuzzy PID tuning controllers based on static gain calculation of linear sub- models and controller scaling factors. The effectiveness of the proposed method was demonstrated on two specific case of processes considered, which included CSTR process. It maintained that the proposed approach provided a considerable reduction in the tuning time and improving the performance of processes whose operating point changes.

Vishnon et al [10] carried out a study on controller performance evaluation for concentration control of isothermal continuous stirred tank reactor. A comparative analysis of conventional PID controller and fuzzy controller performance was studied based on time domain analysis. The performance evaluation was performed in terms of percentage overshot, delay time, rise time, setting time, peak time, Integral square of error (ISE), Integral absolute error (IAE), Integral time absolute error (ITAE). The performance analysis revealed that the hybrid fuzzy provided a satisfactory control effect than conventional controller.

Allwin et al [11] carried out comparison of conventional controller with model predictive controller for CSTR process. It compared the performance of PID controller with MPC controller in the closed loop temperature control of a CSTR process. It stated that the result obtained from the simulation conducted showed that the MPC controller provided better temperature control with zero percentage overshoot and minimum setting time compared to conventional PID controller.

Debnath and Tripsthi [12] carried out a case study to optimize design in linear CSTR using multiple model predictive control approach. It developed a control strategy for a nonlinear CSTR process, its multiple model predictive control (MMPC) technique. The MMPC was implemented using MATLAB software. Performance comparison was out for the CSTR process with single MPC controller and multiple MPC controllers. The developed scheme provided better disturbance rejection than single MPC technique.

III. SYSTEM DESIGN AND CONFIGURATION

This section presents the mathematical equation representing the dynamic model of a CSTR. The model is presented in Eq. (1) in the form of a transfer function. The detail mathematical design and modelling of the considered CSTR process can be obtained in Upadhyay and Singla [13]. Also, in this section is the design and configuration of MRAC control loop in Simulink for CSTR process control.

A. Dynamic Model of CSTR Process

The transfer function representing the dynamic model of CSTR process is given by:

$$G_p(s) = \frac{2.7s + 2.742}{s^2 + 1.33s + 0.4968} \quad (1)$$

The transfer function model provides approximate linear relationship between the input and output. It is widely applied in control system engineering to define the dynamic characteristics industrial processes. It is well used in CSTR model representation to approximate the complex nonlinear relationship of the energy balance and mass equations.

B. Model Reference Adaptive Control

The design specifications of CSTR process for concentration control are: Maximum overshoot = 5%; and Settling time ≤ 3s.

In this paper, the technique adopted provides a systematic way for automatically adjusting the parameters of a CSTR process to maintain a desire level of performance. The control technique is adaptive, and designing it requires that the control system performance be known, the dynamic model of the process be established and a suitable controller design approach that will ensure that the objective of design is realized [14].

There are several approaches to developing the adjusting mechanism when implementing a MRAC. They are: Massachusetts Institute of Technology (MIT) rule, Lyapunov theory and augmented error theory. In this paper, the MIT rule will be used.

Using the MIT rule, the equations for the error and cost function are presented as follows:
Let the difference between the actual output of the process and output of the referenced model be defined as the error e:

$$e = \theta - \theta_{model} \quad (2)$$

The equation for the cost function θ_c is defined as:

$$J(\theta_c) = \frac{1}{2}e^2 \quad (3)$$

The cost function can be minimized such that the change in the parameter θ_c can be maintained in the direction of the negative gradient of J, and that is

$$\frac{d\theta_c}{dt} = -\gamma \frac{\partial J}{\partial \theta_c} = -\gamma e \frac{\partial e}{\partial \theta_c} \quad (4)$$

The partial derivative expression $\partial e / \partial \theta_c$ is called the sensitivity derivative. It shows the change in error with respect to parameter θ_c. Equation (4) describes the change in the parameter θ_c with respect to time so as to be able to reduce the cost function to zero. Where the adjustable gain, gamma γ represents a positive quantity which indicates the gain of the adaptation mechanism of the controller.

Now the transfer function of the CSTR process is $KG(s)$, where K is a parameter whose value is unknown and $G(s)$ is a second order system with a known transfer function (Eq. 1). The objective is to design a controller such that the CSTR process could track a reference model whose transfer function, $G_m(s) = K_o G(s)$, where K_o is a parameter whose value is known.

Definitions:

$$E(s) = KG(s)U(s) - K_o G(s) U_c(s)$$
(5)

Stating a control law:

$$U(s) = \theta_c \times U_c(s) \quad (6)$$

Substituting Eq. (6) into Eq. (5) and taking partial differential yields:

$$\frac{\partial E(s)}{\partial \theta_c} = KG(s)U_c(s) = \frac{K}{K_o}\theta_{\mathrm{model}}(s) \qquad (7)$$

Combining Eq. (4) and Eq. (7) yields

$$\frac{d\theta_c}{dt} = -\gamma e\frac{K}{K_o}\theta_{\mathrm{model}} = -\gamma' e\theta_{\mathrm{model}} \qquad (8)$$

Equation (7) provides the law for adjusting the parameter θ_c and the Simulink model of the control loop.

It is desired to generate the reference model. In order to do this, a second order transfer function is selected because the process under consideration is a second order system. Hence [14]:

$$G_m(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \qquad (9)$$

Where ω_n, ζ are the natural frequency response and the damping ratio of the system? They are obtained as follows:

$$M_p = e^{-\pi\zeta/\sqrt{1-\zeta^2}} \qquad (10)$$

Where M_p is the peak value which is equal to 5 %? Substituting this value into Eq. (10) gives the damping ratio ζ as 0.69. Equation (11) below defines the relationship between settling time T_s, the damp ratio ζ, and the natural frequency response, ω_n.

$$T_s = \frac{4}{\varsigma\omega_n} \qquad (11)$$

Substituting the value $T_s = 2s$ seconds and $\zeta = 0.69$ into (11) gives the value for ω_n as 2.90. Substituting these values into Eq. (9) yields

$$G_m(s) = \frac{8.41}{s^2 + 5.8s + 8.41} \qquad (12)$$

C. System Configuration

The MATLAB/Simulink block models of the control system for CSTR process considering uncompensated control loop and compensated control loop are shown in Fig. 1 and Fig. 2. Figure 3 is the complete simulation programme for performance analysis in terms of integral square error (ISE), integral absolute error (IAE), and integral time absolute error (ITAE).

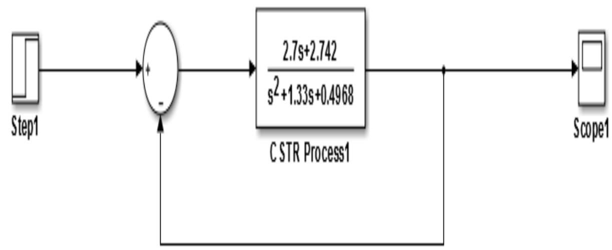

Fig. 1 Simulink model of uncompensated CSTR process

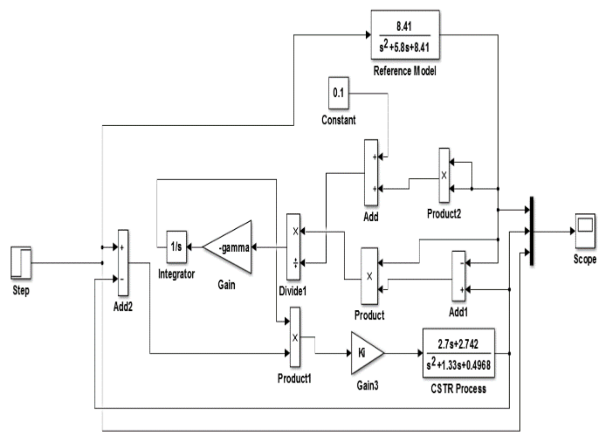

Fig. 2 Simulink model of compensated CSTR process

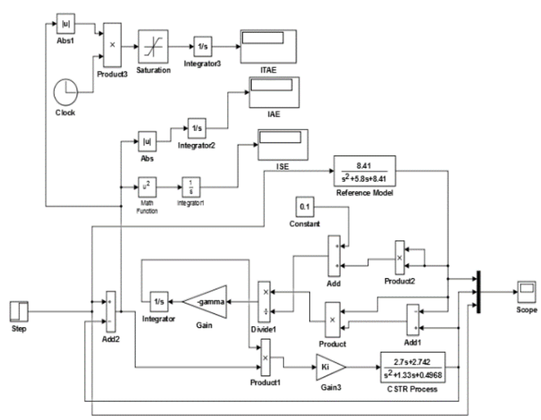

Fig. 3 Complete simulation programme

IV. SIMULATION RESULT AND DISCUSSION

A. System Configuration

In this section the results obtained from the simulations conducted in MATLAB/Simuliknk environment are presented. The simulation test was carried out considering condition for which CSTR process is not compensated and when it is compensated. The simulatio for uncompensated CSTR process is carried out to examine the response performance characteristics of the system when a controller has not been integrated with the control loop as shown in Fig. 4. In Fig. 5, the simulation result of the compensated system is presented. The compensated control simulation is carried out further by adjusting the adaptive gain parameter within the range of $5 \le \gamma' \le 25$ as shown in Fig. 6. The performance analyis of the MRAC controller is examined in terms of ISE, IAE and ITAE as presented in Table 1.

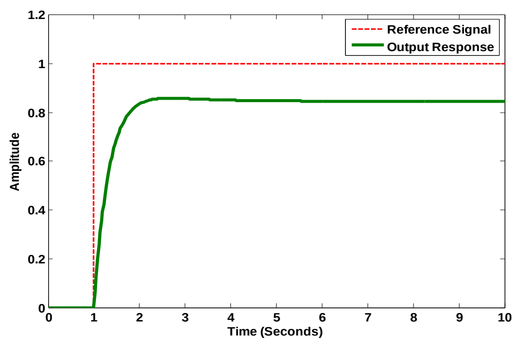

Fig. 4 Step response of uncompensated CSTR process

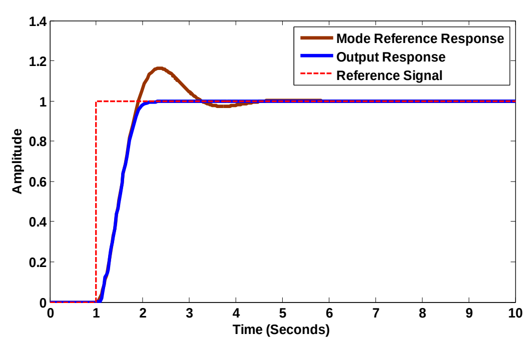

Fig. 5. Step response of compenated CSTR process

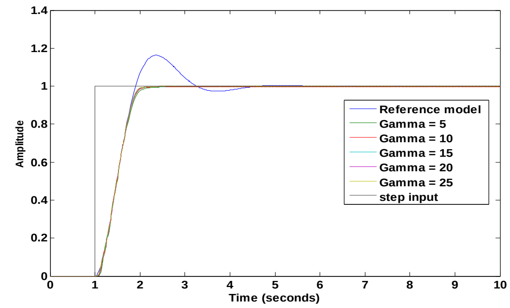

Fig. 6. Step response of compenated CSTR process (with adjusted gain parameter)

TABLE I. PERFORMANCE ANALYSIS FOR MRAC CONTROLLED CSTR PROCESS

	Gain Value of Adaptive Mechanism				
Perform a-nce index	$\gamma' = 5$	$\gamma' = 10$	$\gamma' = 15$	$\gamma' = 20$	$\gamma' = 25$
ISE	0.3392	0.3353	0.3337	0.3329	0.3324
IAE	0.4918	0.4742	0.4672	0.4633	0.4608
ITAE	0.5227	0.4488	0.4198	0.4044	0.3945

B. Discussion

The results of the implementation of a Model Reference Adaptive Controller (MRAC) for CSTR process show that at the time when the control loop has not been compensated, the output response in terms of the concentration is unable to track the desired input, in this case, unit step input (Fig. 4). It means that if the CSTR process is allowed to run without being regulated, the output concentration of the process will not meet the expected value required for effective chemical processing. This highlights the need for a system that will enhance the CSTR process to meet the expected output concentration.

An MRAC is deigned and added to the control loop of CSTR process. The simulation result in Fig.5 shows that the output response of CSTR process is largely improved. Also from the response plot shown in Fig.5, the controller ensures that effective tracking of the desired concentration in terms of step input is realized.

In Fig. 6, the robustness of the MRAC control technique is examined by adjusting gain parameter of the adaptive law. It can be seen from the output responses that at each gain parameter selected, robust tracking is achieved. The performance analysis in Table 1 shows that as the gain increases from 5 to 25, the error decreases as indicated by the ISE, IAE and ITAE values. This indicates that with gamma adjusted to 25, a more improved and robust tracking is obtained.

V. CONCLUSION

This paper has presented design of adaptive controller for CSTR process. The mathematical model of a CSTR process is obtained and implemented in MATLAB/Simulink. A reference model which the plant must followed or matched to is selected using the second order transfer function model since the CSTR process considered is a second order system. A Simulink model of the designed adaptive controller is developed. Simulation test carried out by adjusting the gain parameter of adaptive control indicated that the controller achieved robust tracking for each gain value selected. This means that the designed MRAC effectively reduced the tracking error.

REFERENCES

[1] M. Danish, M. K. . Almesfer, and M. Rashid, "Effect of Operating Controller for a CSTR Process," Internal Journal of Engineering Research and Application, vol. 5, No. 2, pp. 74–78, 2015.

[2] A. L. Pablo, and A-L. Ricardo, "Dynamic Nonlinear Feedback for Temperature Control of Continuous Stirred Tank Reactor with Complex Behaviour," Journal of Applied Research and Technology, Vol. 7, No. 2, 202-217, 2009

[3] D. Zhao, O. Zhu, and J. Dubbeldam, "Terminal Sliding Mode Control for Continuous Stirred Tank Reactor," Chemical Engineering Research and Design, Vol. 47, No. 22, 8741-8753, 2015.

[4] H. Seki, and Y. Naka, "Optimizing Control of CSTR/Distillation Column Processes with one Material Recycle," Industrial and Engineering Chemistry Research, Vol. 47, No. 22, 8741-8753, 2008

[5] M. Darius, and S. Sivagmasundari, "Design and implementation of Controller for a CSTR Process," International of Emerging Technology in Computer Science and Electronics, Vol. 23, No. 1, 175-183, 2016

[6] N. Maheshwari, N. Jain, A. Jingar, and M. Suthehar, "Design and Analysis of PID Controller for CSTR Process," International Journal of Science Engineering and Technology Research, Vol. 5, No. 2, 600-603, 2016.

[7] M.A.S. Aboelela, R.H.M. Hennas, H.T. Dorrah, "Design and Implementation of a PID Controller for a Continuous Stirred Tank Reactor (CSTR) System using particle Swarm Algorithms Conference Paper, 1-12, 2015 https://www.researchgate.net/publication/281068326

[8] N. Khanduja, "CSTR Control by using Model Reference Adaptive Control and PSO," International Journal of Mechanical, industrial and Aerospace Science, Vol. 8, No. 12, 2144-2149, 2015

[9] E.R. Jhon, H.G. Victor, E.C. Jorge, "A Tuning Proposed for direct fuzzy PID Controllers Oriented to industrial Continuous Processes," Preprints of the 3rd IFAC Conference on Advances in Proportional – Integral Derivative Control, 2018.

[10] V. Vishnoi, S. Padhee, and G. Kaur, "Controller Performance Evaluation for Concentration Control of Isothermal Continuous Stirred Tank Reactor," International Journal of Scientific and Research Publications, Vol. 2, No. 6, 1-7, 2012.

[11] S. Allwin, S.N. Biksha, S. Abirami, H. Kala, A.P. Udhaya, "Comparison of Conventional Controller with Model Predictive Controller for CSTR Process," International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, Vol. 3, No. 9, 11934-11941, 2014.

[12] S. Debnath, and V.K. Tripathi, "A case study to optimized Design in linearization of Non-linear CSTR Using Multiple Model Predictive Control Approach," International Journal of Engineering Science and Computing, 6(7), 8682-8686, 2016.

[13] R. Upadhyay, and R. Singla, "Analysis of CSTR Temperature Control with Adaptive and PID Controller (A Comparative Study)," IACSIT International Journal of Engineering and Technology, Vol. 2, No. 5, 453-458, 2010

[14] P. C. Eze, C. A. Ugoh, C. P. Ezeabasili, B. O. Ekengwu, L. E. Aghoghovbia, "Servo Position Control in Hard Disk Drive of a Computer Using MRAC Integrating PID Algorithm," American Journal of Science, Engineering and Technology, Vol. 2, No. 4, 97-105, 2017.