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Design of Model Predictive Controller for Fluid catalytic Cracking Unit

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Abstract: FCCU plays the most vital role in modern refinery process because it has been used for producing more economic refinery products. The implementation of control algorithms for such MIMO system is often complicated due to continuous variations in process dynamics. This is mainly due to the change in operating point and the characteristics of nonlinear dynamic coupling. Since the conventional PID controller is a linear controller, it is efficient only for a limited operating range when it is applied to a nonlinear process. MPC controller can control highly interactive systems with many control variables and most importantly, MPC provides a systematic method of dealing with constraints on inputs and states. The proposed controller aims to maintain desired temperature of reactor and regenerator sections of fluid catalytic cracking unit. The proposed scheme offers good dynamic performance than GA tuned PID controller.

Keywords: Fluid Catalytic Cracking Unit, GA tunedPID Controller, MPC Controller

1. INTRODUCTION

Fluid Catalytic Cracking Unit is the most important conversion process where heavy oils are converted into lighter products used in petroleum refineries. The largest volume of products are fuel oil and gasoline (petrol). Process control applications to the petroleum industries are the basics of the development of heavily invested industries. The modelling and control of cracking process is complex. The complex nature of the feed oil assumes a three lumped kinetic mechanism for the treatment of cracking process.

Various control strategies such as PI control [4], Decentralized PID control [5], Robust PID [7], Non-linear PID control [8], Genetic algorithm [10], fuzzy Control [12], MPC [14] and some other intelligent controllers have been proposed in the past for Fluid Catalytic Cracking Unit.

In this paper MPC controller for Fluid Catalytic Cracking Unit has been designed using MATLAB/ Simulink. Simulation results show the effectiveness of the proposed control scheme in reducing theerror and suppressing the undesirable effects of the system process.

Organization of the paper is as follows. Fluid Catalytic Cracking Unit and its modelling is briefly explained in section 2 and 3. Proposedcontrol scheme is presented in section 4. Simulation resultsare discussed and presented in section 5. Finally, the lastsection concludes the paper.

2. FLUID CATALYTIC CRACKING UNIT

Fluid Catalytic Cracking Units are central process in many petroleum refineries that converts heavy oil i.e. crude oil into some useful products, such as, LPG, gasoline, light diesel etc., by cracking. It is one of the

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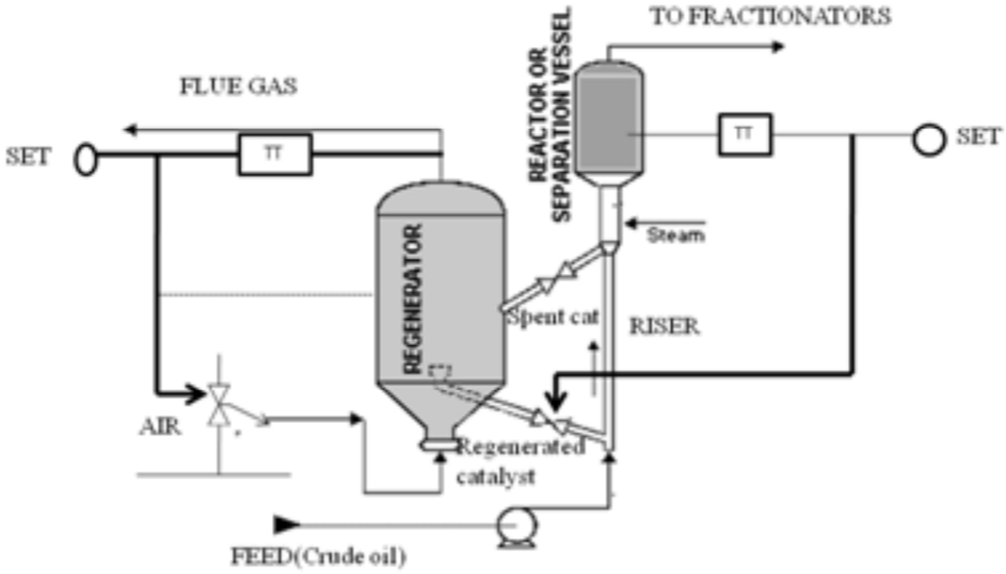


Figure 1: General setup of fluid catalytic cracking unit

typical complex system [1], which consists of interconnected subsystems, Reactor/Riser where the feed gasoil is cracked into gasoline i.e. endothermic cracking reaction and coke deposits takes place and Regenerator where the carbon is burned off the spent catalyst(exothermic) by using air.

A typical FCC unit and its control flow diagram is shown in Figure 1. Feed stock arrives at the bottom of riser, vaporises and cracks into products and the cracked products go to a fractionating system for separation into gasoline, light gases etc, Carbon is burned off the spent catalyst in the regenerator i.e. catalyst deactivation and the regenerated catalyst i.e. fresh catalyst returns to the reactor carrying sufficient heat to supply the heat requirements of the endothermic cracking reaction, thus repeats the cracking cycle.

In the presence of catalyst, the cracking is accelerated thousands of times and takes place at low temperatures than thermal cracking, which are advantages economically. The Operating temperature of the reactor is about 776K – 820K and regenerator is about 998K–1080K.

3. MODELLING OF FCCU

The aim of the proposed work is to control the temperature of FCCU unit, the mathematical model of FCCU unit is designed using energy balance equation.

A number of simplified assumptions have been made in order to formulate energy balance in reactor and regenerator which include,

1. Neglecting the conduction, convection, and radiated terms.
2. Heat of reaction and heat of combustion are constant.

3.1. Reactor Model

The residence time of feed in the riser is only a few seconds, and hence ideal reactor model is used [3]. The energy balance around the reactor will be,

Input stream – [Output stream-Heat of reaction] = Rate of Accumulation
Heat of Reg. catalyst + Heat of Feed + Heat of Steam = Rate of
{Heat of Effluent – Heat of Spent Catalyst + Heat of reaction} Accumulation

$$F_{rc}Cp_{rc}T_{reg} + F_f Cp_f T_f + F_{st}H_{st} - F_p Cp_p T_{rea} - F_{sc}Cp_{sc}T_{rea} + \Delta H_R = (M_p Cp_p + M_{sc}Cp_{sc})\frac{dTrea}{dt} \qquad (1)$$

3.2. Regenerator Model

The catalyst residence time in the regenerator is generally around 10 to 20 min. It is common to assume that the temperature and the amount of coke on catalyst are uniform throughout the regenerator.

$$\left.\begin{array}{c}\text{Input stream – [Output stream + Heat of combustion] = Rate of}\\ \text{Accumulation Heat of Spent catalyst + Heat of Air–\{Heat of Combustion = Rate of}\\ \text{AccumulationHeat of Reg. Catalyst – Heat of Flue gases\}}\end{array}\right\}$$

$$F_{sc}Cp_{sc}T_{rea} + F_aCp_aT_a + \Delta H_c - F_{rc}Cp_{rc}T_{reg} - F_{fl}Cp_{fl}T_{reg} = (M_{rc}Cp_{rc} + M_{fl}Cp_{fl})\frac{dTreg}{dt} \tag{2}$$

Where,

Subscripts

rc = Regenerated Catalyst

f = Feed or Gasoil

st = Steam

sc = Spent Catalyst

p = Product

a = Air

fl = Flue gas

Superscript

F = Mass Flow Rate

CP = Specific Heat Capacity

T = Temperature

M = Mass

H = Enthalpy

ΔHR = Heat of Reaction

ΔHC = Heat of Combustion

4. CONTROLLER STRUCTURE

4.1. Pid Controller

PID Controller is the most commonly used conventional controller in industries. The difference between measured process variable and desired set point is calculated by PID controller as an error. The controller attempts to minimize the error by adjusting the manipulated variable of the process.

MIMO systems are controlled by decentralized control system that consists of independent SISO controllers. The structure of decentralized PID controller for an $n \times n$ system with a decentralized feedback control structure as shown in Figure. 2.where *r*, *u* and *y* are the set point, control signal, output respectively.

Decoupling Control System

Chemical processes usually have two or more controlled outputs, requiring two or more manipulated variables. Two characteristics should be investigated to design of control systems for MIMO process.

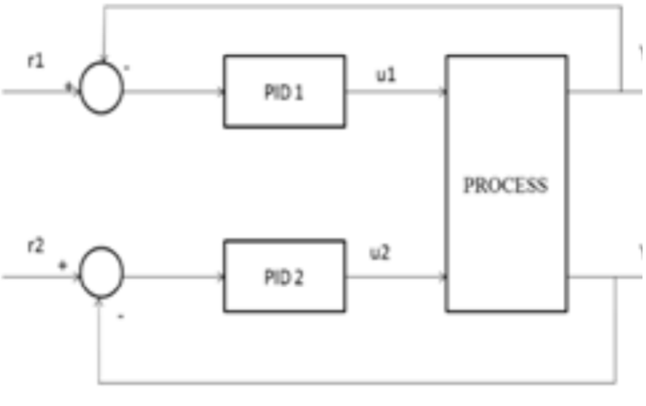


Figure 2: Decentralized PID

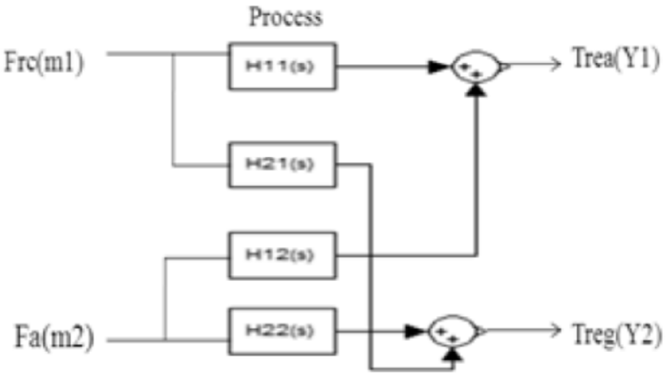


Figure 3: Process with interaction

1. Interaction among the loops
2. The number of feasible, alternative control loop configuration that gives minimal interaction (RGA analysis)

Relative Gain Array (Rga)

The RGA is a matrix of numbers, in which ij^th^ elements in the array are called relative gain (λij). It is the ratio of the steady state gain between the i^th^ controlled variable and j^th^ manipulated variable, when all other manipulated variables are constant and the steady state gain between the same two variables where all other controlled variables are constant.

The RGA provides exactly such a methodology, whereby we can select pairs of input / output variables in order to reduce the amount of interaction among the resulting loops.

The RGA is computed as follows,

$$\frac{\left(\Delta Y_i / \Delta M_j\right)M}{\left(\Delta Y_i / \Delta M_j\right)Y} = \lambda_{ij} \tag{3}$$

$$\lambda = \begin{array}{c} \\ \\ \end{array}\begin{array}{cc} Frc & Fa \\ \end{array}$$

$$\lambda = \begin{bmatrix} \lambda 11 & \lambda 12 \\ \lambda 21 & \lambda 22 \end{bmatrix}\begin{array}{l} Trea \\ Treg \end{array} \tag{4}$$

The FCCU is composed of two controlled outputs and two manipulated inputs as shown in fig.3., the input and output relationships are given by,

$$T_{rea}\,(s) = H_{11}\,(s)\,F_{rc}\,(s) + H_{12}\,(s)\,F_a\,(s) \tag{5}$$

$$T_{reg}\,(s) = H_{21}\,(s)\,F_{rc}\,(s) + H_{22}\,(s)\,F_a \tag{6}$$

Where $H_{11}(s)$, $H_{12}(s)$, $H_{21}(s)$, $H_{22}(s)$ are the four transfer functions relating the two outputs and two inputs shown in Figure 3

Design Of Non-interacting Control Loop

The RGA indicates how the inputs should be coupled with the outputs to form loops with the outputs to form loops with the smaller amount of interaction. The purpose of decouplers is to cancel the interaction effects between the two loops and thus gives non-interacting control loops as shown in Figure 4.

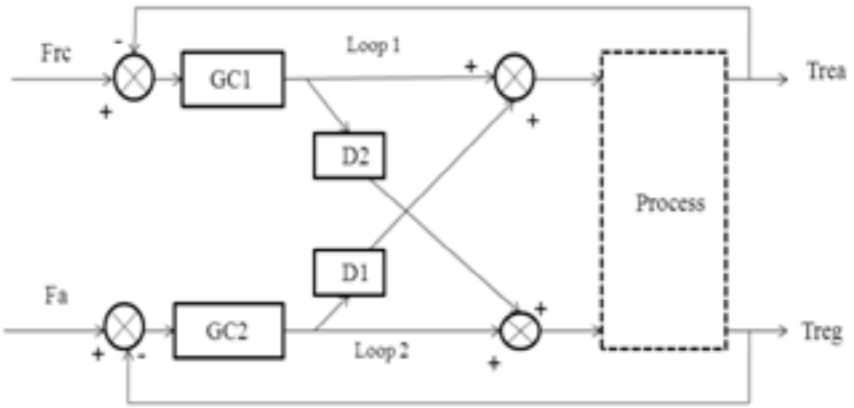


Figure 4: Implementation of decoupler

4.2. Mpc Controller Structure

Model predictive control (MPC) is an excellent method of process control that has been use in the chemical process industries. Model predictive controllers depend on dynamic models of the process, most often linear empirical models obtained by system identification.

MPC allows the current timeslot to be optimized, while keeping future timeslots in account. This has been achieved by optimizing a finite time-horizon, but only implementing the current timeslot [19]. MPC has the ability to anticipate future events and can take control actions accordingly.The block diagram of proposed controller structure is shown in the Figure 5. The control architecture consists of a model and optimizer.

The models used in MPC are generally designed to represent the behavior of complex dynamical systems. MPC control algorithm is not often needed to provide adequate control of simple systems, due to its complexity, which are often controlled conventional PID controllers. Whereas MPC can replace Common dynamic characteristics such as large time delays and higher order dynamics that are difficult to control by PID controllers.

In Figure 6 the MPC controller has to optimize over *P* future sampling periods and calculate *M* future moves when it rejects all but the first move in each cycle. Indeed, under certain conditions a controller using $P = M = 1$ would be equal to one using $P = M = \infty$. More often, however, the horizon values have an important effect.

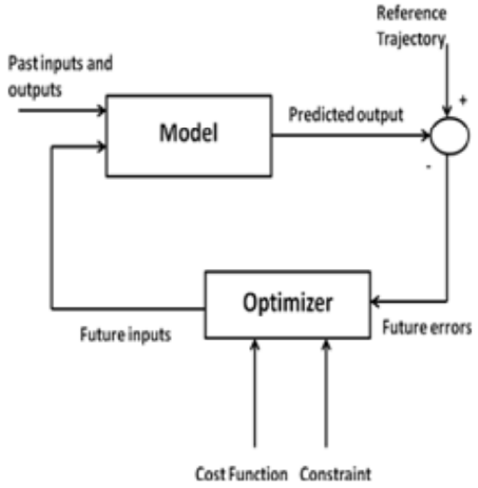


Figure 5: Block diagram of MPC controller

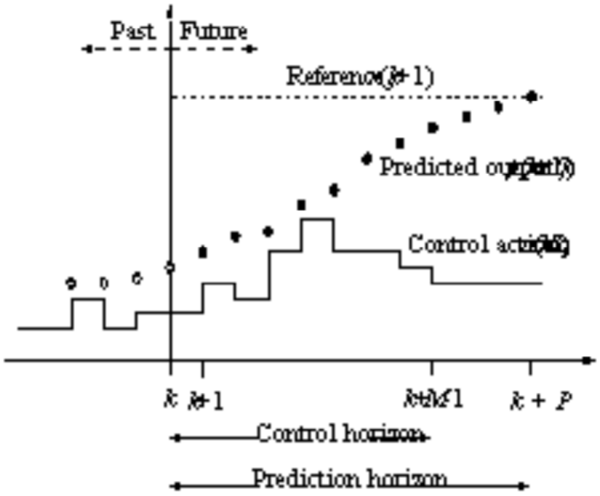


Figure 6: Prediction and Control Horizon of MPC

5. RESULTS AND DISCISSION

The mathematical model of FCCU plant was obtained using energy balance equation from equations (1) and (2). The FCCU mathematical model has been developed from the above data given in Table 1.

5.1. Closed Loop Response Of Fccu

The decentralized PID controller has been designed in MATLAB/Simulink tool. The optimum PID controller parameters were tuned using real coded Genetic Algorithm Technique,(RGA), and the corresponding ISE graph is shown in Figure8 and it represents an optimized value soon after 30 generations.The ISE value which is one of the most determining performance index is monitored for various generations and the performances criteria (ISE) has become constant after a number of consecutive generations for closed loop of GA based PID controller.

Table 1
Steady state Parameters of FCCU

Parameters	*Value*
Specific heat capacity of Regenerated catalyst	1.005KJ/KgK
Mass Flow rate of feed(Gasoil)	51.25Kg/Sec
Specific heat capacity of feed	3.1335KJ/KgK
Temperature of feed	420K
Mass Flow rate of steam	20.5Kg/Sec
Enthalpy of Steam	2802KJ/Kg
Mass Flow rate of Spent catalyst	463.37Kg/Sec
Specific heat capacity of Spent catalyst	1.9KJ/KgK
Mass of Spent catalyst	2316.86Kg
Mass of regenerated catalyst	4547.93Kg
Specific heat capacity of Air	1.05KJ/KgK
Temperature of air	773K
Heat of reaction	506.2KJ/Kg
Heat of combustion	6929.8KJ/Kg
Mass Flow rate of flue gases	75.00Kg/Sec
Mass Flow rate of product	62.95Kg/Sec

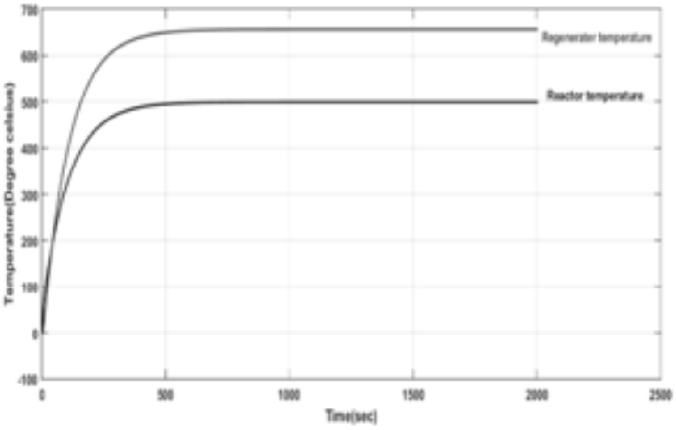


Figure 7: Open loop Response

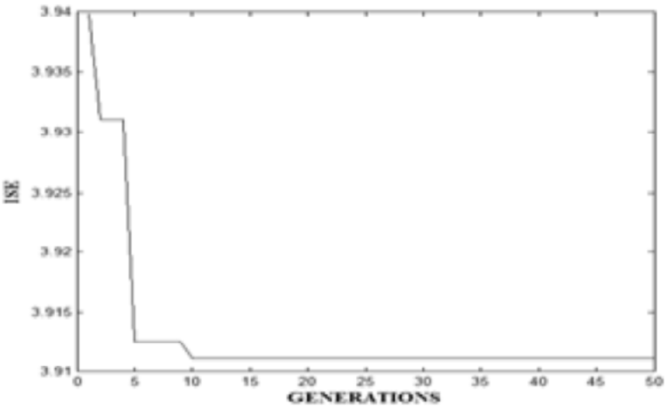


Figure 8: ISE graph for GA tuned PID for 50 generation

5.2. Servo Response Of GA Tuned PID Controller

The performance of FCCU for GA tuned PID is shown in Figure 9 and Figure 10.From the response, it is observed that the reactor and regenerator temperature follow the given set points (Servo response).

5.3. Servo Regulatory Response Of GA Tuned PID Controller

Simulation studies have been carried out to show the disturbance rejection capability of GA tuned PID controller with changing set points. A step disturbance is introduced to F_{rc} at 170Seconds and removed at 320 seconds. The servo with regulatory responses of t for GA tuned PID is shown in Figure 11 and Figure 12

5.4. Close Loop Response Of MPC

Using MATLAB Simulink tool MPC controller has been designed for FCCU unit. Tuning parameters for the MPC controller was shown in Table 2.

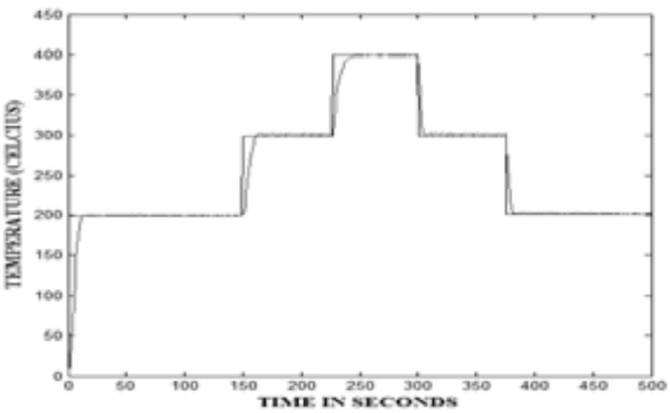


Figure 9: Servo response of reactor temperature of GA tuned PID Controllertemperature

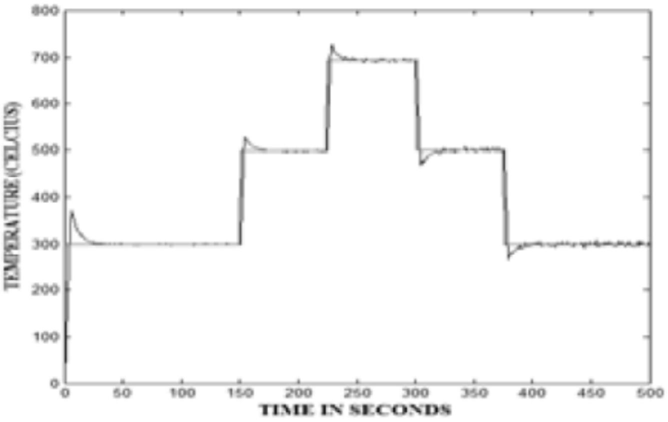


Figure 10: Servo response of regenerator of GA tuned PID controller

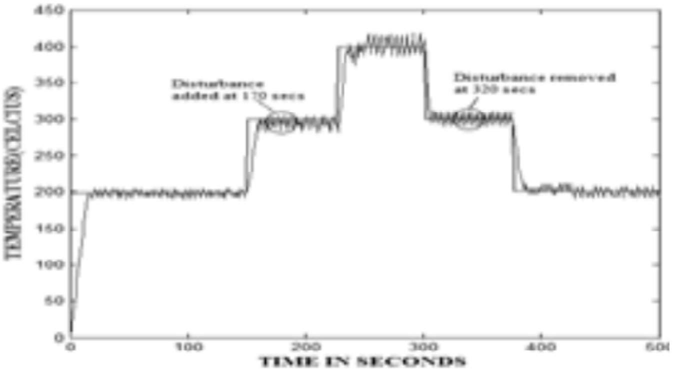


Figure 11: Servo with regulatory response of reactor temperatureforGA PID controller

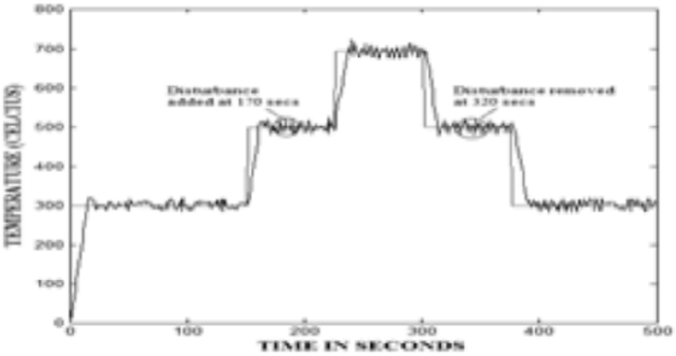


Figure 12: Servo with regulatory response of tuned regenerator temperature for GA tuned PID controller

Table 2
Tuning Parameters

Parameters	*Value*
Control Horizon	2
Prediction Horizon	10
Control Interval	1
Input Weight	0
Output Weight	1.0
Response Scale	0.8

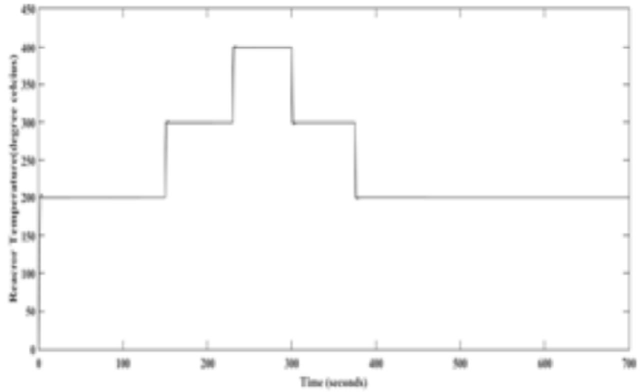


Figure 13: Multistep Response of MPC for Reactor Temperature

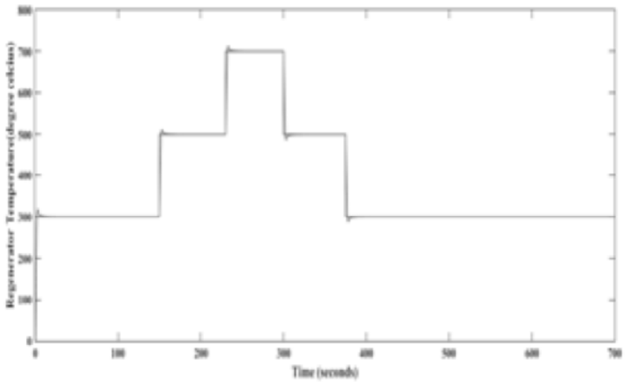
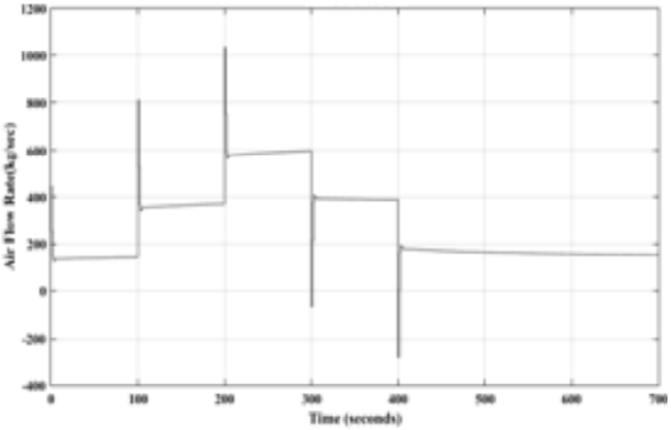


Figure 14: Multistep Response of MPC for Regenerator Temperature



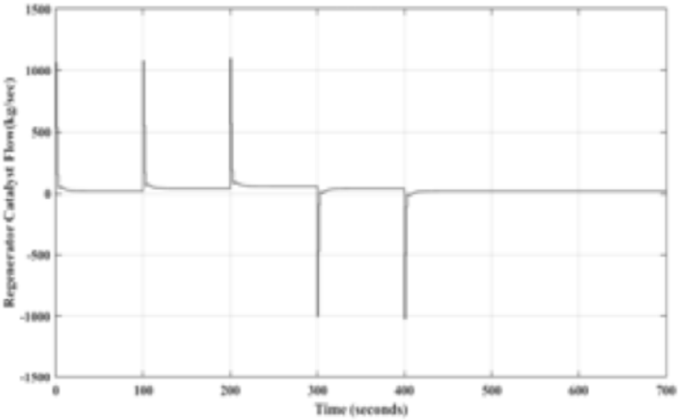


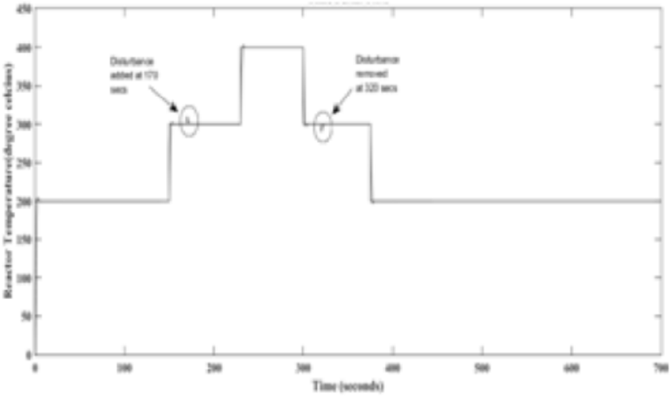
Figure15: Control signal of Regenerator

Figure 16: Control signal of Reactor

Figure 13 to Figure 16 shows the close loop response of MPC controller and corresponding control signal of FCCU plant. From the responses it is observed that MPC controller has faster settling time and tracking capability. It is also observed that the response of FCCU takes 5 seconds and 13 seconds to settle at their specific set point limits of Reactor and regenerator Temperature.

5.5. Servo Response Of Mpccontroller

Simulation studies have been carried out to show the disturbance rejection capability of MPC controller with changing set points. A step disturbance is introduced to F_{rc} at 170Seconds and removed at 320 seconds. Figure 17 to Figure 20 shows the closed loop response of MPC controller and corresponding control signal of FCCU plant.



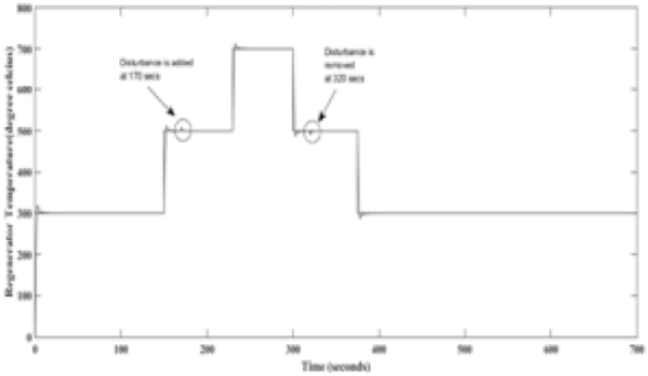
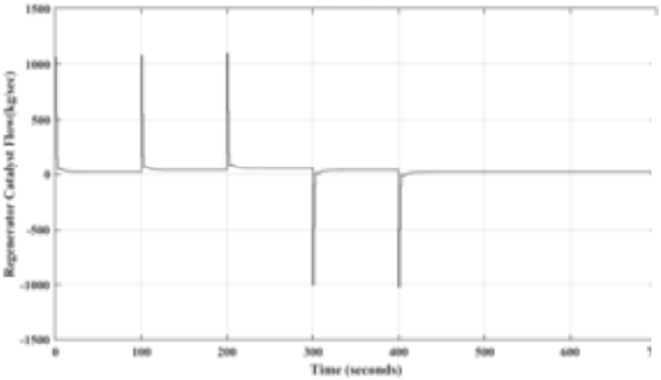


Figure 17: Servo with regulatory response of reactor temperature for MPC

Figure 18: Servo with regulatory response of regeneratortemperature for MPC



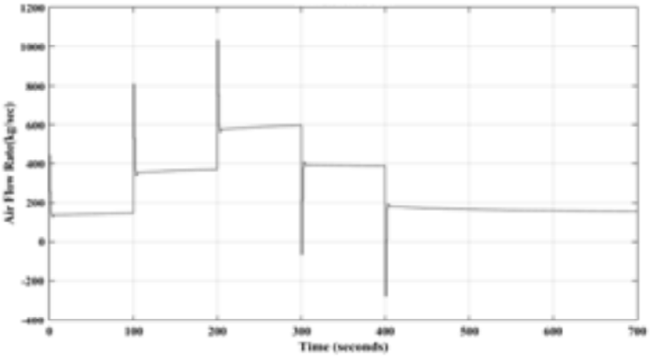


Figure 19: Control signal for Reactor

Figure 20: Control signal for regenerator

From the above responses of PID controller and MPC controller the performance indices for both controllers were compared and tabulated in Table 3 and Table 4

Table 3
Performance indices for PID and MPC in servo response

Control variable	*PID*			*MPC*		
	ISE	*IAE*	*ITAE*	*ISE*	*IAE*	*ITAE*
Trea	1.42e+5	1792	3.057e+5	4.412e+4	584.6	1.295e+4
Treg	2.08e+5	3134	1.53e+6	9.574e+4	971.5	1.974e+5

Table 4
Performance indices for PID and MPC for servo with regulatory response

Control variable	*PID*			*MPC*		
	ISE	*IAE*	*ITAE*	*ISE*	*IAE*	*ITAE*
Trea	1.42e+5	1791	3.057e+5	3.545e+4	521.7	9.588e+4
Treg	2.08e+5	3134	1.53e+6	1.20e+5	1088	2.126e+05

From the above table it is observed that the MPC controller has better performance indices than conventional PID controller.

5. CONCLUSION

In this work, a linear MPC scheme is adopted to study the behavior of highly interactive reactor and regenerator temperature loops of FCCU units. Tuning of MPC controller parameters was done by trial and error method.It has been observed that the performance indices namely ISE, IAE, ITAE in servo and servo with regulatory response of MPC control scheme was better than GA tunedPID control scheme.

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