Australian Journal of Basic and Applied Sciences, 8(17) November 2014, Pages: 265-273

AENSI Journals

Australian Journal of Basic and Applied Sciences

ISSN:1991-8178

Journal home page: www.ajbasweb.com

Performance Assessment of PID and MPC Control Algorithm subject to Servo Tracking and Disturbance Rejection

[1]Wincy Pon Annal and [2]Jovitha Jerome

[1]Department of Electronic and Instrumentation Engineering, Government College of Technology, Coimbatore, Tamil nadu, India.
[2]Department of Instrumentation and Control Systems Engineering, PSG College of Technology, Coimbatore, Tamil nadu, India.

ARTICLE INFO

Article history:
Received 19 August 2014
Received in revised form
19 September 2014
Accepted 29 September 2014
Available online 10 November 2014

Keywords:
Non linear Model Predictive Control, pH neutralization process, Integral Square Error, waste water treatment, set point tracking, disturbance rejection

ABSTRACT

The pH neutralization is a highly nonlinear and time-varying process, which has different operating regimes. The control objective in neutralization process is to maintain the pH value at the prescribed level by controlling the flow rate of both acid and base. The classical PID control scheme does not deal with constraints. It also requires proper tuning to meet the requirements. MPC has the knowledge of handling constraints with optimization and control. Hence, MPC turns into a more powerful algorithm to meet the requirements of pH neutralization process. Model predictive controller is employed for this process to vary the controller parameters for each operating point so that the set point can be tracked effectively in all operating regimes. An additive load disturbance is applied to the flow rate of acid and base to check if the regulatory response can also be obtained with satisfactory performances. The simulation results are used to evaluate and compare the performance of both the controllers (PID and MPC). The results are compared using time domain specifications, computational time and performance index like Integral Square Error (ISE).

To Cite This Article: Wincy Pon Annal and 2Jovitha Jerome., Performance Assessment of PID and MPC Control Algorithm subject to Servo Tracking and Disturbance Rejection. ***Aust. J. Basic & Appl. Sci.,*** *8(17): 265-273, 2014*

INTRODUCTION

The control objectives are to drive the system to different pH conditions (tracking control) or to regulate the effluent pH value despite the disturbance by manipulating the flow rate of titrating stream as stated by Derar (2009). The pH neutralization is normally a difficult process to control, due to the non-linearity caused by the titration curve as reported by Asuero and Michalowski (2011) mainly when strong acids and bases are involved.

The pH process control has been widely used in chemical industry, optical industry, wastewater treatment, biotechnological industries and environmental protection. For instance, the pH of effluent streams from wastewater treatment plants must be maintained within stringent environmental limits as stated by Michael and Dale (1994). Tight control of pH is also critical in the production of pharmaceuticals. However, high performance and robust pH control is often difficult to achieve due to non-linear and time varying characteristics. These processes can exhibit severe static nonlinear behaviour because the process gain can vary several orders of magnitude over a modest range of pH values. Also, the titration curve may be time varying due to changes which are not measured in the buffering capacity as reported by Rosdiazli (2008).

The increase in plant complexity and strict constraints in terms of environmental and other performance requirements provide a significant challenge in the control applications. The inherent and severe non linearity of a pH neutralization process is a major source of difficulty in terms of robust and stable control system design.

Due to the influence of serious non-linearity, time delay, and strong interference in pH neutralization process, the control of the pH neutralization process has been one of the most difficult problems in relative fields as stated by Xiaohui *et al*. (2011). Thus, the research of control and identification in pH neutralization process is very important.

Duraid (2003), proposed set range intelligent controllers, to maintain the pH range in industrial waste water. Gomez and Baeyens (2004), have proposed predictive control to a pH neutralization process model obtained from wiener model identification. A nonlinear model predictive control framework based on the sequential quadratic programming (SQP) algorithm was implemented to control the pH value by Sanaz *et al*. (2009). A comparative approach is done with linear and non-linear adaptive control, even soft computing, thus neural network is also implemented for this process.

Corresponding Author: Wincy Pon Annal, Department of Electronic and Instrumentation Engineering, Government College of Technology, Coimbatore, Tamil nadu, India.

The increasing complexity of the process by themselves, the requirement of product quality and the environmental regulations has lead the process industries to search for more reliable, robust, accurate, flexible, and efficient control of the plant which leads to the implementation of advanced control techniques in process industries.

MATERIALS AND METHODS

pH Neutralization Process:

Neutralization is a process of reducing the acidity or alkalinity by mixing acids or bases to produce neutral solution. Acidic or basic wastewater must be neutralized prior to discharge for minimum impact on environment. Neutralization is considered as a preparatory step in the wastewater treatments because many of the subsequent wastewater treatment are pH dependent. The regulations on the quality of industrial waste have become increasingly stringent in recent years. Industrial waste must be neutralized before it is discharged as effluent from manufacturing plant.

A process effluent composed of variety of components has a varying titration curve that defeats effort to attain smooth neutralization on a sound economic basis unless the pH controller can adapt to feedback control conditions ranging from oscillatory to over damped. In the system of waste water management, controlling the pH of an effluent stream is challenging because it is very unstable at neutral condition.

In waste water treatment, the pH control is very difficult because the composition of flowing stream changes at every instant.The exact information about the flow, pH, and alkalinity or acidity of the waste water and about how much and how quick these parameters change are required for proper control system design. A typical pH control system consists of one or more reactors, mixer, measuring elements, controllers and reagent delivery systems.

The gain of the system at the equivalence point for the strong acid or strong base system is very high and it occurs at a pH of 7, which is neutral pH. Control of this system near pH 7 would place very high demands both on the accuracy of the control system and on the range ability of the reagent delivery system. Because of the lower gain near neutrality the weak acid or weak base system is easier to control.

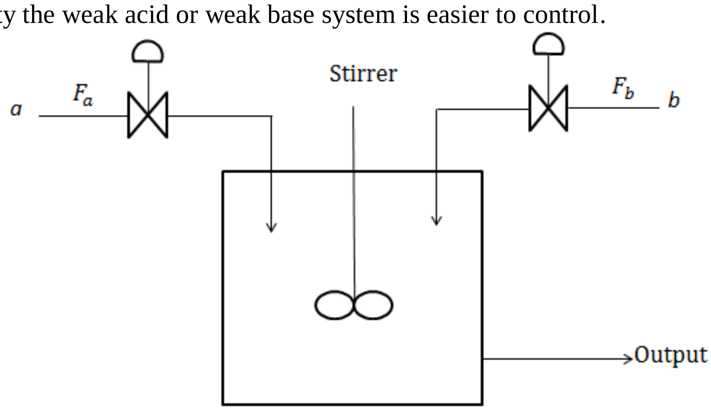

Fig. 1: Schematic Diagram of pH Neutralization Process

The design of the neutralization process depends mostly on factors like reaction tank size, which can affect the neutralization performance (e.g. a large vessel is required when low solubility reagents such as calcium lime are present.) for which the retention time should be minimized, mixing and agitation for complete elimination of the area of unreacted reagent which if not done properly may lead to insufficient mixing and excessive cycling and poor pH control, the relative location of the vessel inlet, outlet, and measurement probe location for maximum speed of response and the reagent delivery system and reagent addition point location for close pH control.

pH is only a measure of the concentration of dissociated hydrogen ions present in a solution. When a solution contains a weak acid, most of its hydrogen ions are un dissociated. This reasoning can be applied to a weak alkali by considering hydroxide ions (OH-) instead of hydrogen ions (H+). The different operating region is selected based on static characteristics of pH neutralization performance. The schematic diagram of pH neutralization process is shown in Figure 1. The pH is related to the concentration of the ions [H+] through the following logarithmic function as stated by Jacobs *et al*. (1980).

$$\mathrm{pH} = -\log_{10}[\mathrm{H}^+] \tag{1}$$

The neutralization of a strong acid effluent (HCl) in a CSTR by a strong base (NaOH) is considered here. A first order dynamics model is used with titration curve as the nonlinearity. The reactions that occur are,

$$\begin{cases} \mathrm{HCl} + \mathrm{NaOH} \rightarrow \mathrm{H_2O} + \mathrm{NaCl} \\ \mathrm{H^+} + \mathrm{OH^-} \rightarrow \mathrm{H_2O} \end{cases} \tag{2}$$

Australian Journal of Basic and Applied Sciences, 8(17) November 2014, Pages: 265-273

The possible amount of effluent to be neutralized is defined mainly by the concentration of the reactants. The ionic concentrations of $[Cl^-]$ and $[Na^+]$ in the CSTR can be related to the flows of acid F_a, and of base F_b, and to the input concentrations of $[Cl^-_{in}]$ and $[Na^+_{in}]$, according to the following equations, provided the mixture is perfect and instantaneous.

$$V\frac{d}{dt}[Cl^-_{in}].F_a - [Cl^-_{in}].F_{out} \quad (3)$$

$$V\frac{d}{dt}[Na^+] = [Na^+_{in}].F_b - [Na^+].F_{out} \quad (4)$$

where, V is the volume of liquid in the CSTR.

The electro-neutrality equation must be satisfied by the concentrations.

$$[Na^+] + [H^+] = [Cl^-] + [OH^-] \quad (5)$$

which, together with the dissociation equation for water:

$$[H^+].[OH^-] = K_W = 10^{-14} \quad (6)$$

relates these concentrations to$[H^+]$ and therefore to pH.

The difference of the ionic concentrations X is

$$X \equiv [OH^-] - [H^+] \quad (7)$$

that combined with equation (5) results in:

$$X \equiv [[Na^+] - [Cl^-] \quad (8)$$

Combining these equations results in

$$\begin{cases} [H^+] = \frac{X}{2}.\left(\sqrt{1+\frac{4.K_W}{X^2}} - 1\right) & \text{IF } X > 0 \\ [H^+] = -\frac{X}{2}.\left(\sqrt{1+\frac{4.K_W}{X^2}} + 1\right) & \text{IF } X < 0 \\ [H^+] = \sqrt{K_W} & \text{IF } X = 0 \end{cases} \quad (9)$$

The equation describing the process dynamics is obtained by subtracting (3) from (4) and using (8), resulting in:

$$V\frac{dX}{dt} = [Na^+_{in}].Q_b - [Cl^-_{in}].Q_a - X.Q_{out} \quad (10)$$

The time constant τ is given by,

$$\tau = \frac{v}{Q_{out}} \quad (11)$$

It is dependent on the residence time.

Equations (3), (4) and (10) correspond to the pH neutralization model. It is considered that the CSTR is at room temperature.

The open loop response of the system is shown in Figure 4. The model of the system taken is represented in transfer function as

$$G(s) = \frac{344.9910}{108.25s+1} \quad (12)$$

The discrete-time state space model of the system is given by,

$$\dot{x} = 0.9991x + 0.1u \quad (13)$$

$$y = 3.1870x \quad (14)$$

Closed Loop Control Schemes:

For the purpose of controlling pH neutralization process, the closed loop control schemes discussed are Proportional Integral Derivative (PID), and Model Predictive Control (MPC) controller design .The design of each control scheme is presented in detail.

PID Controller Design:

In PID controller, the control signal, $u(t)$ is produced based on the combination of proportional, integral and derivative action. The proportional term (P) is directly related to the error signal, $e(t)$, integral term (I) corresponds to integral of the error and derivative term (D) is based on derivative action on the error. The resulting signals are weighted and summed to obtain the control signal, $u(t)$, which is applied to the plant model. The schematic block diagram of PID control scheme is shown in Figure 2.

Australian Journal of Basic and Applied Sciences, 8(17) November 2014, Pages: 265-273

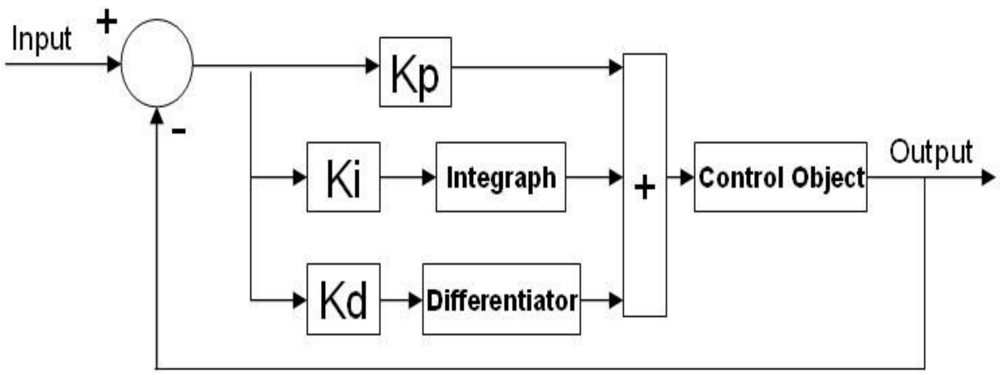

Fig. 2: Block Diagram of PID Control Scheme

A mathematical representation of the PID controller is

$$u(t) = K_p e(t) + K_i \int_0^t e(t)d\tau + K_d \frac{d}{dt} e(t) \quad (15)$$

where, u(t) is the control input to the plant model, e(t) is the error which is the difference between actual output y(t) and reference input r(t), K_p is the proportional gain, K_i is the integral gain and K_d is the derivative gain. Because the system response is dependent on controller parameters, settling of these parameters is significant. Among the different tuning approaches available for the determination of these gain values, Ziegler-Nichols technique is utilized to tune the system.

Model Predictive Control (MPC):

The model predictive control is an advance optimal control strategy that is based on the explicit use of system state space model to predict the controlled process variables over a certain time horizon and the prediction horizon as reported by Prakash and Senthil (2008). The structure of a model predictive controller is shown in Figure 3.The dynamic matrix control algorithm is discussed in this section.

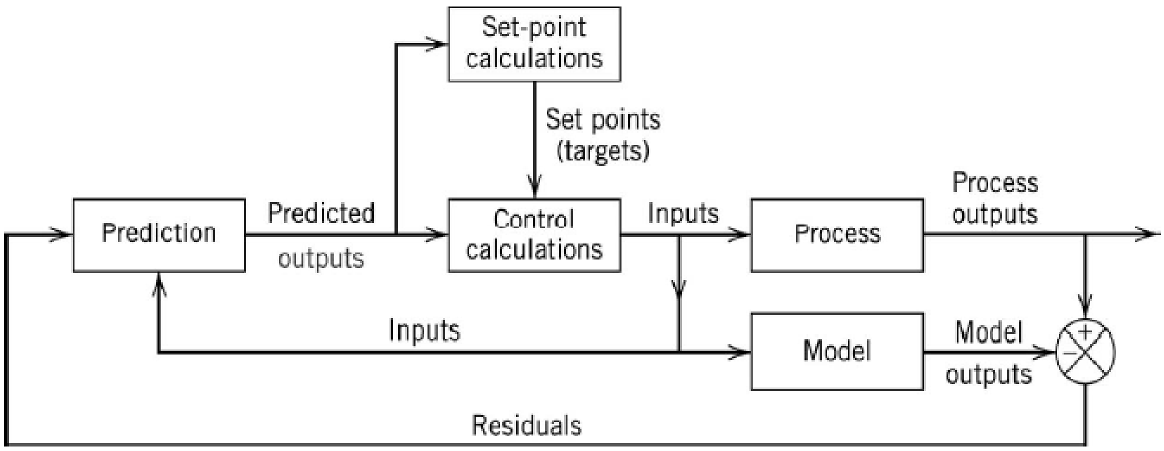

Fig. 3: Structure of a Model Predictive Controller

Based on a step response model, it has the form

$$\hat{y}_k = \sum_{i=1}^{N-1} S_i \Delta u_{k-i} + S_N u_{k-N} \quad (16)$$

The additive disturbance is the difference between the measured output and model prediction. The corrected prediction obtained from additive difference is

$$\hat{y}_k^c = \hat{y}_k + d_k \quad (17)$$

The corrected predicted output for j^{th} step in future is

$$\hat{y}_{k+j}^c = \hat{y}_{k+j} + \hat{d}_{k+j} \quad (18)$$

$$\hat{y}_{k+j}^c = \sum_{i=1}^{j} S_i \Delta u_{k-i+j} + \sum_{i=j+1}^{N-1} S_i \Delta u_{k-i+j} + S_N u_{k-N+j} + \hat{d}_{k+j} \quad (19)$$

The effect of past and future control moves can be separated as

$$\hat{y}_{k+j}^c = S_1 \Delta u_{k+j-1} + S_2 \Delta u_{k+j-2} + \dots + S_j \Delta u_k$$
$$+ S_N \Delta u_{k+j-1} + S_{j-1} \Delta u_{k-1} + S_{j+2} \Delta u_{k-2} + \dots + S_{N-1} \Delta u_{k-N+j+1} + \hat{d}_{k+j} \quad (20)$$

The correction term is assumed as constant in the future

$$\hat{d}_{k+j} = \hat{d}_{k+j-1} = \cdots = d_k = y_k - \hat{y}_k \quad (21)$$

A prediction horizon of m steps and a control horizon of n steps yields

$$\hat{Y}^c = S_f \Delta u_f + S_{past}\, \Delta u_{past} + S_N\, u_p + \hat{d} \quad (22)$$

The difference between set-point trajectory and future Prediction is

$$r - \hat{Y}^c = r - \left[S_{past}\, \Delta u_{past} + S_N\, u_p + \hat{d}\right] - S_f \Delta u_f \quad (23)$$

that yields

$$E^c = E - S_f \Delta u_f \quad (24)$$

The objective function is

$$\emptyset = (E^c)^T E^c + (\Delta u_f)^T W \Delta u_f \quad (25)$$

Minimization of this objective function will provide

$$\Delta u_f = \left[\left(S_f^T W_e\, S_f + W_u\right)^{-1} S_f^T W_e\right] E \quad (26)$$

The current and future control move vectors are proportional to the unforced error vector

$$\Delta u_f = K_1 * E \quad (27)$$

where,

$$K_1 = \left(S_f^T W_e\, S_f + W_u\right)^{-1} S_f^T W_e \quad (28)$$

The deviations in u values are determined by minimizing an objective function including the predicted future errors. Here, m represents prediction horizon and n represents control horizon, r represents the future set-point trajectory and $\hat{y}$ represents the vector of controlled outputs. The control variable of MPC controller is calculated based on the predicted output. Therefore model needs to reflect the dynamic behaviour of the plant as precisely as possible.

Results:

For the pH neutralization process, the sampling time is taken as 5 seconds. The main objective of the process is to maintain the pH value. The servo response, the tracking efficiency of the controller is discussed in this section.

The open loop response of the pH neutralization process is shown in figure 4 for various values of concentration of input feed.

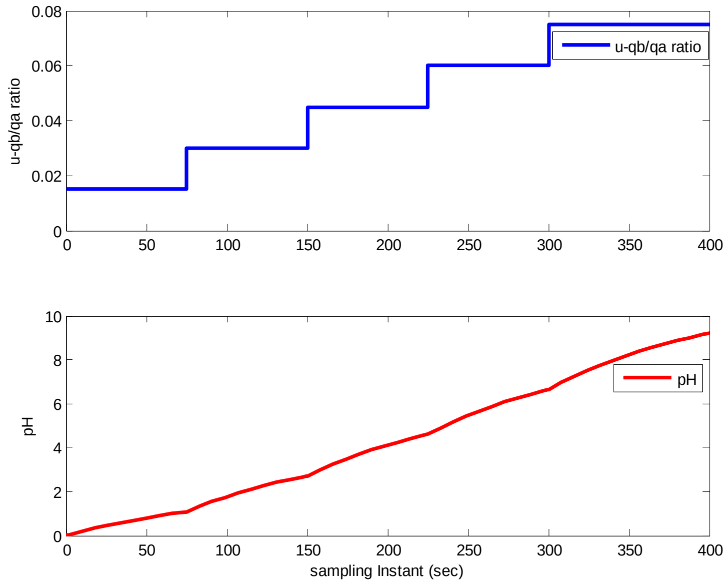

Fig. 4: Open Loop Response of pH Neutralization Process

The PID controller is tuned using Ziegler Nichlos method and the values of K_p, K_i, and K_d are tabulated as shown in table 1.

Table 1: PID Controller Parameters for pH Neutralization Process

K_p	K_i	K_d
2.35	8.92	0.0187

Australian Journal of Basic and Applied Sciences, 8(17) November 2014, Pages: 265-273

The set point tracking response of the pH process for both PID and MPC controllers are shown in figure 5 and the corresponding controller response is shown in figure 6.

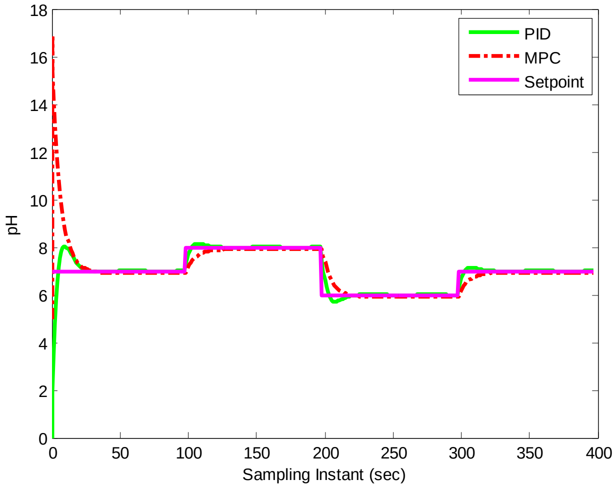

Fig. 5: Set point Tracking Response of PID Controller and MPC controller for the pH Neutralization Process

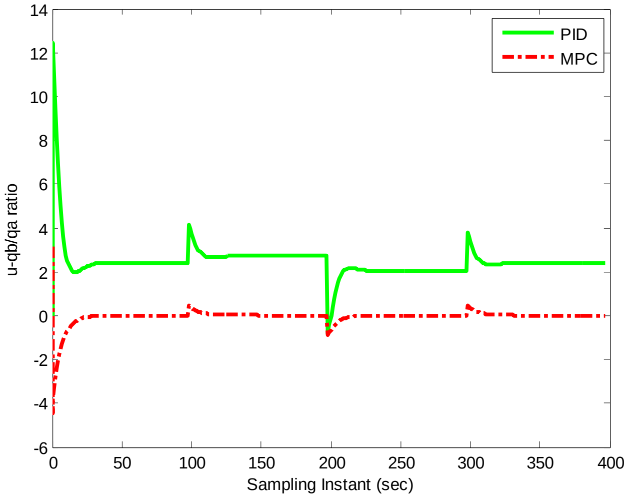

Fig. 6: Controller response for set point tracking of PID controller and MPC controller for the pH Neutralization Process

Figure 7 shows the PID controller and the MPC controller response which helps to reject the disturbance that has occurred in the process and their corresponding controller responses are shown in figure 8

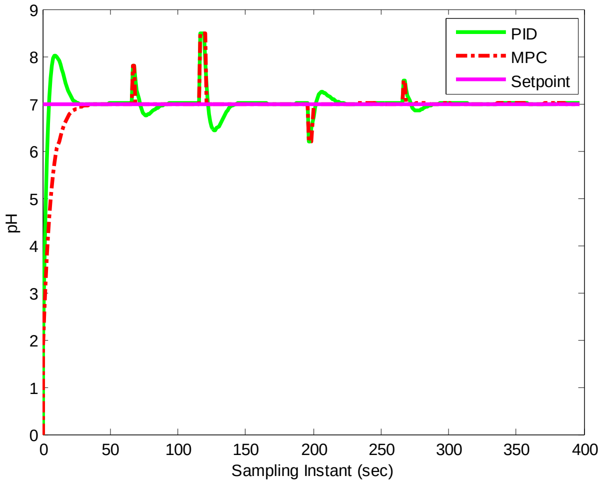

Fig. 7: Disturbance Rejection Response of PID Controller and MPC controller in pH Neutralization Process

Australian Journal of Basic and Applied Sciences, 8(17) November 2014, Pages: 265-273

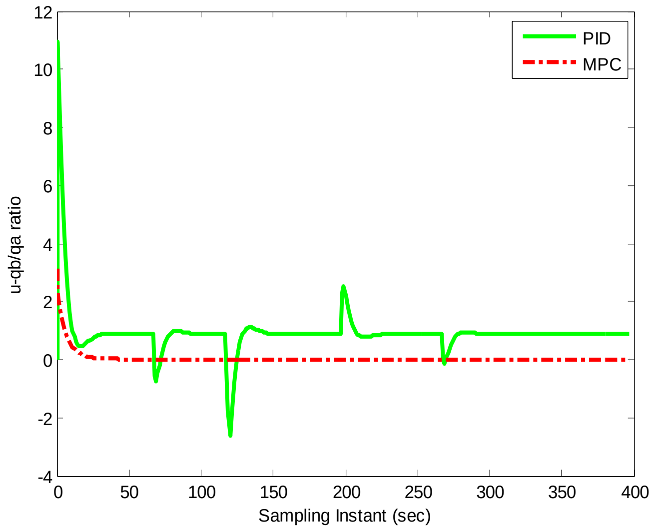

Fig. 8: Controller response for disturbance rejection of PID controller and MPC controller for the pH Neutralization Process

The tables 2, 3 and 4 gives details about MPC controller settings, performance analysis of both PID and MPC controllers when set point is tracked and when disturbance is rejected respectively.

Table 2: MPC Controller Settings for pH Neutralization Process

Parameters	Values
Prediction Horizon (m)	10
Control Horizon (n)	1
Weighting Factor (W_e)	12
Weighting Factor (W_u)	7
Sampling Time	5

Table 3: Setpoint Tracking - Comprehensive Performance Analysis of all Closed Loop Configurations for pH Neutralization Process

Control Schemes	Time Domain Specifications			Performance Indicator	Computational Complexity
	Overshoot (%)	Rise Time (Sec)	Settling Time (Sec)	Integral Square Error (ISE)	Computational Time (Sec)
PID	9.3460	2.0588	18.2907	2.347	0.0063
MPC	144.2254	4.1898	8.287	1.935	0.0243

Table 4: Disturbance Rejection - Comprehensive Performance Analysis of all Closed Loop Configurations for pH Neutralization Process

Control Schemes	Time Domain Specifications			Performance Indicator	Computational Complexity
	Steady State Error (%)	Rise Time (Sec)	Time taken to anticipate the disturbances (sec)	Integral Square Error (ISE)	Computational Time (Sec)
PID	0.76	3.6414	8	2.7570	0.0072
MPC	0	6.1898	5	2.0821	0.0440

Discussions:

PID controller:

Set point Tracking:

The simulated set point tracking response is illustrated in Figure 5. The PID configuration provides the highest oscillations while tracking the reference value. It is the slowest response with respect to settling time (T_{ST}) and also it does not handle any constraints. However, it shows the speed in the rise time (T_{RT}) because of its simplicity in design. The steady state error for PID control scheme is less than 1% and may be considered negligible. The complete performance analysis of PID control scheme such as time domain specifications, performance indicator and total computational time are tabulated in Table 3.

Disturbance Rejection:

The simulated disturbance rejection response along with the load disturbance profile is illustrated in Figure 7. To obtain the regulatory response, the load disturbance is given to the process. It takes about 6 seconds to track the set point after the occurrence of load disturbance. However, the PID configuration does not provide smooth response under the load profile. For each disturbance that has occurred in the process, the controller involves an undershoot.

MPC Controller:

The simulated MPC controller settings are tabulated in Table 2. The weighted matrices W_e and W_u are tuned using the formulae $W_u = B^T B$ and $W_e = C^T C$ respecively. It is also noted that the weighted matrices W_e and W_u should be less to get the reliable output and minimum steady state error. $0 \leq u \geq 80$ is the constraints imposed on the manipulated variable (i.e. compressor voltage).

Setpoint Tracking:

The simulated setpoint tracking response of MPC is illustrated in Figure 5. The MPC configuration provides no oscillations and smooth response while tracking the set point value. The MPC control scheme gives zero steady state error in set point tracking under output constraints. It is the fastest response with respect to settling time (T_{ST}) and rise time (T_{RT}) and it also handles constraints. But, it shows poor performance in computational complexity because of its complex design. When compared to classical PID scheme, MPC gives minimum ISE value. The complete performance analysis of MPC control scheme such as time domain specifications, performance indicator and total computational time is tabulated in Table 3.

Disturbance Rejection:

The simulated disturbance rejection response along with the load disturbance profile of MPC is illustrated in Figure 7.To obtain the regulatory response, the load disturbance is given to the process. It takes very less time, in seconds, to track the set point after the occurrence of load disturbance. Also, the MPC configuration ensures no steady state error and a smoother response under the load profile. But, it shows poor performance in computational complexity for regulatory response.

Conclusion:

In pH neutralization process, the aim is to maintain pH value in the prescribed limit. As pH neutralization is a nonlinear process it has different operating regions. So the controller parameters need to be tuned for each operating region. Thus instead of a simple PID controller, MPC controller is implemented**,** which provides satisfactory performance in all the operating regions. The performance of MPC controller is compared with PID.

The design and development of an appropriate optimal control scheme for pH neutralization is done. The performance of each controller is evaluated in terms of time domain specifications, Integral square error and computational time and MPC is found to provide a better performance in all aspects when compared to PID controller.

REFERENCES

Derar Issam Abd Al Kareem, 2009. Implementation of neural control for neutralization process, Masters thesis, University of Technology.

Asuero, A.G. and T. Michalowski, 2011. Comprehensive Formulation of Titration Curves for Complex Acid-Base Systems and its Analytical Implications. Critical Reviews in Analytical Chemistry, 41(2): 151-187.

Michael, A., Henson and Dale E. Seborg, 1994. Adaptive Nonlinear Control of a pH Neutralization Process. IEEE Transactions on Control Systems Technology, 2: 169-182.

Rosdiazli Ibrahim, 2008. Practical modelling and control implementation studies on a pH neutralization process pilot plant, Doctorate thesis, University of Glasgow.

Xiaohui Chen, Jinpeng Chen, and Bangjun Lei, 2011. Identification of pH Neutralization Process Based on the T-S Fuzzy Model. Advances in Computer Science, Environment, Ecoinformatics and Education, 2: 579-585.

Duraid, F. Ahmed, 2003. On-line control of the neutralization process based on fuzzy logic, Ph.D. Thesis, University of Baghdad.

Gomez J.C. and E. Baeyens, 2004. Wiener Model Identification and Predictive Control of a pH Neutralization Process. IEE Control Theory Appllication, 51: 329-338.

Sanaz Mahmoodia, Javad Poshtana, Mohammad Reza Jahed-Motlaghb, and Allahyar Montazeria, 2009. Nonlinear Model Predictive Control of a pH Neutralization Process Based on Wiener–Laguerre Model. Chemical Engineering Journal, 146: 328-377.

Jacobs, O.L.R., M.A. Hewkin and C. While, 1980 . Online Computer Control of pH in an Industrial Process. IEE Proceedings, 127(4): 161-168.

Zhenpeng Yua, Jiandong Wanga, Biao Huangb, and Zhenfu Bi, 2011. Performance Assessment of PID Control Loops Subject to Setpoint Changes. Journal of Process Control, 21: 1164-1171.

Prakash, J and R. Senthil, 2008. Design of Observer Based Nonlinear Model Predictive Controller for a Continuous Stirred Tank Reactor. Journal of Process Control, 18: 504-514.

Prakash, J and K. Srinivasan, 2009. Design of Nonlinear PID Controller and Nonlinear Model Predictive Controller for a Continuous Stirred Tank Reactor. ISA Transactions, 48: 273-282.

Australian Journal of Basic and Applied Sciences, 8(17) November 2014, Pages: 265-273

Yang, J., X. Li, H.G. Mou, and L. Jian, 2009. Predictive Control of Solid Oxide Fuel Cell Based on an Improved Takagi–Sugeno Fuzzy Model. Journal of Power Sources, 193: 699-705.

Arce, A., D.R. Ramirez, A.J. del Real and C. Bordons, 2007. Constrained Explicit Predictive Control Strategies for PEM Fuel Cell Systems. In the proceedings of Conference on Decision and Control, pp: 6088-6093.