Proportional Integral (PI) Controller for a Process Plant System

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***Abstract*—This paper proposed Proportional; Integral (PI) control strategies for a process plant system using Cohen and Coon and Hagglund-Astron techniques with the Ziegler-Nichols method as a base-line for the tuning of the controllers. The results of the system responses of the designed control schemes were successfully simulated using LABVIEW. Comparing the results showed that controller implemented using the Hagglund-Astrom method was the best this is because during the simulation exercise, the system under control produced an overshoot of 13% and a settling time of 11.4226 seconds. On the other hand, the system tuned using the Cohen and Coon method has an overshoot of 64% and settling time of 18.9149 seconds which are higher than Hagglund-Astrom and Ziegler-Nichols tuning relations.**

Keywords*—PI Controller; Hagglund-Astrom Method; Ziegler-Nichols Method; Cohen and Coon method; Process Plant.

I. INTRODUCTION

Process control involves the regulation of variables in a dynamic system. A process control system maintains a variable in a process at its set-point. A process can be any combination of materials and equipments that produces a desirable result through changes in chemical properties, physical properties or energy. A continuous process produces an uninterrupted flow of product, while a batch process produces an interrupted flow of product. Examples of a process include a home heating system, a dairy processing system, petroleum refining process, food processing plant, fertilizer production plant and so on. The most common controlled variables in a process include pressure, density, flow rate, temperature, viscosity, colour, hardness, PH, and conductivity [1, 2].

Several control modes that can be used are the Proportional (P), Integral (I), Proportional plus Integral (PI), Proportional plus Derivative (PD) and Proportional plus Integral plus Derivative (PID). However, in this study only the PI controller will be used. The primary reason for the integral control is to reduce or eliminate steady state errors, but at the expense of worse transient response. The general forms of PI and PID controllers were as shown in equations (1), (2), (5) and (3), (4), (6) respectively [3-5].

For PI;

$$u(t) = K_p e(t) + K_i \int e(t)dt \quad (1)$$

After Laplace transformation it becomes;

$$U(s) = K_p E(s) + K_i \frac{E(s)}{s} \quad (2)$$

For the PID;

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \quad (3)$$

After Laplace transformation;

$$U(s) = K_p E(s) + K_i \frac{E(s)}{s} + K_d sE(s) \quad (4)$$

In terms of time constants for PI;

$$U(s) = K_p \left[1 + \frac{1}{\tau_i}\right] E(s) \quad (5)$$

And for PID;

$$U(s) = K_p \left[1 + \frac{1}{\tau_i} + \tau_d\right] E(s) \quad (6)$$

$$K_i = \frac{K_p}{\tau_i} \text{ and } K_d = K_p \tau_d \quad (7)$$

Where: u(t) is the actuating signal, e(t); the error signal, K_p; proportional gain, K_i; the integral gain, τ_i; integral time constant and τ_d; derivative time constant.

II. METHODOLOGY

The main purpose of this task is to investigate two PI controllers using the: Cohen and Coon and Hagglund-Astrom PID controller tuning algorithms, in addition to use Ziegler-Nichols tuning relations as a base-line design for the tuning of the proportional and integral gains in the control loop of a process plant and to calculate the PI controller settings using their designs and compare their performances. The process plant model used was as shown by equation (8).

$$G(s)=\frac{2e^{-0.987s}}{2.878s+1} \quad (8)$$

A. Hagglund-Aström Controller

First, the settings for this type of controller are given in details as shown in table I:

TABLE I. HAGGLUND-ASTROM PI CONTROLLER SETTINGS

G(s)	K_p	τ_i
$\frac{Ke^{-\theta s}}{s}$	$\frac{0.35}{K\theta}$	7θ
$\frac{Ke^{-\theta s}}{\tau s+1}$	$\frac{0.14}{K}+\frac{0.28\tau}{\theta K}$	$0.33\theta+\frac{6.8\theta\tau}{10\theta+\tau}$

From table 1 it is clear that the second row is the one that matches the plant model question as a first order system; and the values of K_P and τ_i were determined as shown below: $\theta=0.987000$, τ = 2.878000 and K= 2.000000; from which K_p, K_i and τ_i were obtained as; 0.478227, 0.259775 and 1.84093 respectively. The PI controller transfer function using this method was therefore as shown in equation (9);

$$G_{HA}=0.478227+\frac{0.259775}{s} \quad (9)$$

B. Cohen and Coon PI controller

The transfer function of the process plant is of the form as shown in equation (10);

$$G(s)=\frac{Ke^{-\theta s}}{\tau s+1} \quad (10)$$

Then, K_p and τ_i are determined using equations (11) and (12) respectively, with K=2.000000, τ = 2.878000 and $\theta=0.978000$.

$$K_p=\frac{\tau}{\theta K}\left[0.9+\frac{\theta}{12\tau}\right] \quad (11)$$

$$\tau_i=\frac{\theta\left[30+3\left(\frac{\theta}{\tau}\right)\right]}{9+20\left(\frac{\theta}{\tau}\right)} \quad (12)$$

K_p, K_i and τ_i are obtained as; 1.353820, 0.701057 and 1.93112 respectively. Therefore, the transfer function of Cohen and Coon PI controller is given as;

$$G_{CC}=1.353820+\frac{0.701057}{s} \quad (13)$$

C. Ziegler-Nichols PI controller

This method was suggested as the base-line design to judge the two controller designs which were obtained previously. The reaction curve PID settings for this type of controller were as shown in Table II below:

TABLE II. ZIEGLER-NICHOLS PID TUNING RELATIONS

Controller Structure	Proportional Gain Kp	Integral Time Constant τ_i	Derivative Time Constant τ_d
Case (i) P	$\frac{1}{R_N L}$		
Case (ii) PI	$\frac{0.9}{R_N L}$	3L	
Case (iii) PID	$\frac{1.2}{R_N L}$	2L	0.5L

In this method to get the values of R_N and L is by plotting a graph of the unit step input response of the modeled plant or plant model as large as possible to obtain an accurate measurement for Ziegler-Nichols tuning rules. R_N is the ratio of the maximum slope of the unit step response to the reference input signal, which is unity in this case and L is the delay time. The slope was found to be 0.7333 and L equal to one second, this makes R_N to be 0.733300 and K_p, τ_i and K_i were 1.227000, 3.00000 and 0.409100 respectively. The transfer function of the Ziegler-Nichols PI controller becomes:

$$G_{ZN}(s)=1.227000+\frac{0.409000}{s} \quad (14)$$

The Ziegler-Nichols method was used to determine the controller parameters K_p and K_i which are the proportional gain and integral gain constants respectively, such that the system has good performance.

III. RESULTS AND DISCUSSION

Time responses of the closed loop system to a unit step inputs with the different controllers are displayed in Fig. 1 and the time response parameters were as shown in Table III below:

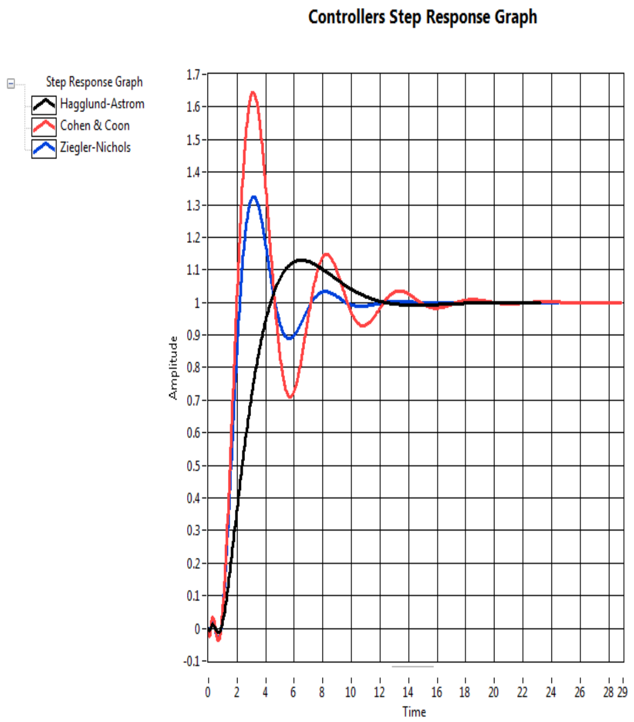

Fig. 1. Unit step response graph of the plant with the different controllers.

TABLE III. PARAMETRIC DATA OF THE THREE CONTROLLERS

PI Settings	Rise Time (s)	Overshoot (%)	Peak time (s)	Settling Time (s)	Peak Value (s)
Hagglund -Astrom	2.4828	13.1	6.4712	11.4226	1.13098
Cohen & Coon	0.7854	66.3	3.1363	18.9149	1.66329
Ziegler-Nichols	0.9405	33.9	3.1664	11.3576	1.33854

From Table III it can be clearly seen that the system with Hagglund-Astrom controller was the best for the system, because it has smallest overshoot of 13.1%, settling time of 11.4226 seconds and the highest peak time of 6.4712 seconds. On the other hand, using the Cohen and Coon tuning relation, the system has faster response with rise time of 0.7854 seconds, higher overshoot of 66.3% and longer settling time of 18.9149seconds. And for the base line that is using the Ziegler-Nichols tuning method; the system has an overshoot of 33.9%, settling and peak times of 11.3576 and 0.9405 seconds respectively.

Bode graphs were plotted by using the Labview software which indicate the gain and phase margins of the system for the three different controllers. The plots show the stability as well as determining the form or amount of corrective measure needed for dynamic compensation. The gain margin (GM) is the amount of gain K that can be added to the system to give 0dB [5] which could be read directly from the Bode plot by measuring the vertical distance between $|KG(j\omega)|$ curve and the $|KG(j\omega)|$ = 1 line at the frequency where the angle of $G(j\omega) = -180^0$. In addition, the phase margin (PM) is the amount of phase that can be added to a system when the gain is 0dB before the phase reaches (-180^0)[5].

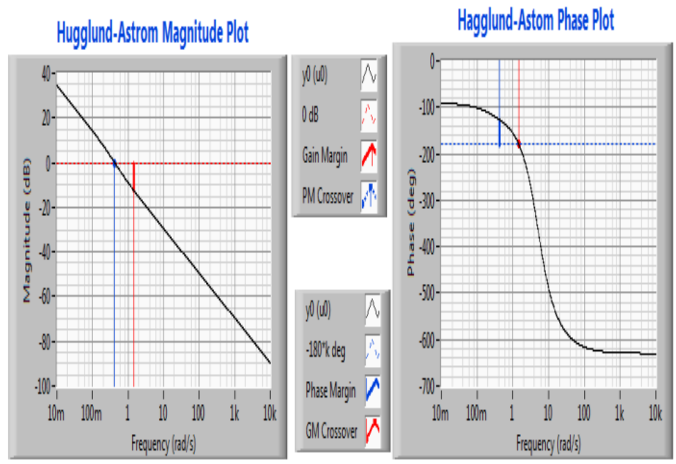

Fig. 2. Magnitude and Phase Plot for the Hagglund-Astrom Control Method.

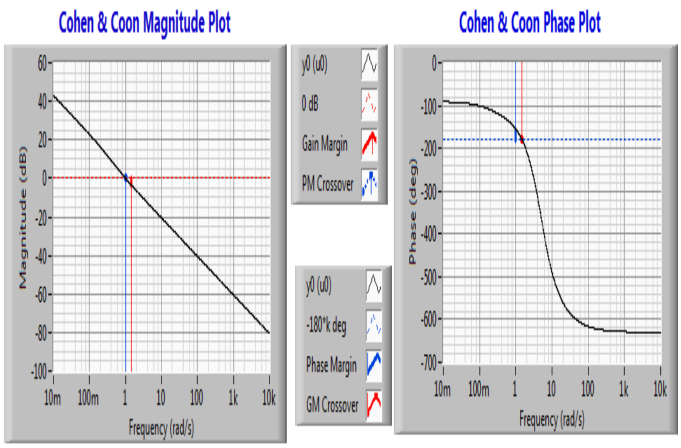

Fig. 3. Magnitude and Phase Plot for the Cohen and Coon Control Method.

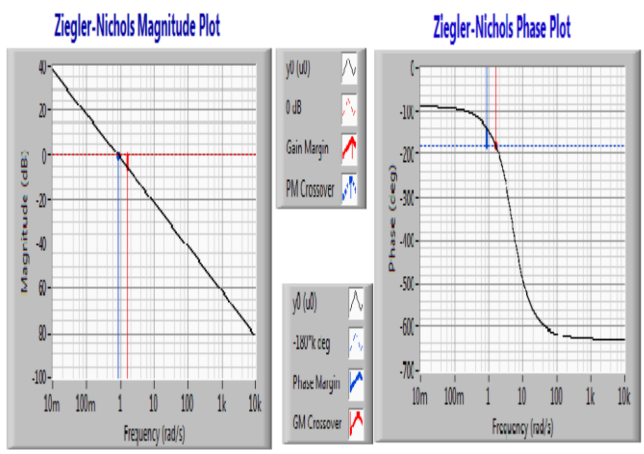

Fig. 4. Magnitude and Phase Plot for the Ziegler_Nichols Control Method.

The magnitude and phase margin plots for the system with the respective PI controllers were shown in Figs. 2 - 4 while their results for gain margin, phase margin, gain margin and crossover frequency were shown in Table IV.

TABLE IV. GAIN AND PHASE MARGINS OF THE CONTROL SCHEMES

PI Controllers	Gain Margin (dB)	Phase Margin (deg)	GM Frequency (Hz)	PM Frequency (Hz)
Hagglund-Astrom	12.5721	53.6223	1.4663	0.4189
Cohen & Coon	3.6827	25.1948	1.4826	1.0007
Ziegler-Nichols	5.4933	42.8767	1.6018	0.8477

From the magnitude and phase margin plots of respective controllers shown above it can be observed that the gain and phase margins are positive, which further confirms the system stability.
A 0.1 (10% of unit step) step disturbance was introduced onto the system with the different controllers at the time of 40s (at steady state). The behavior of the system was displayed in Fig. 5.

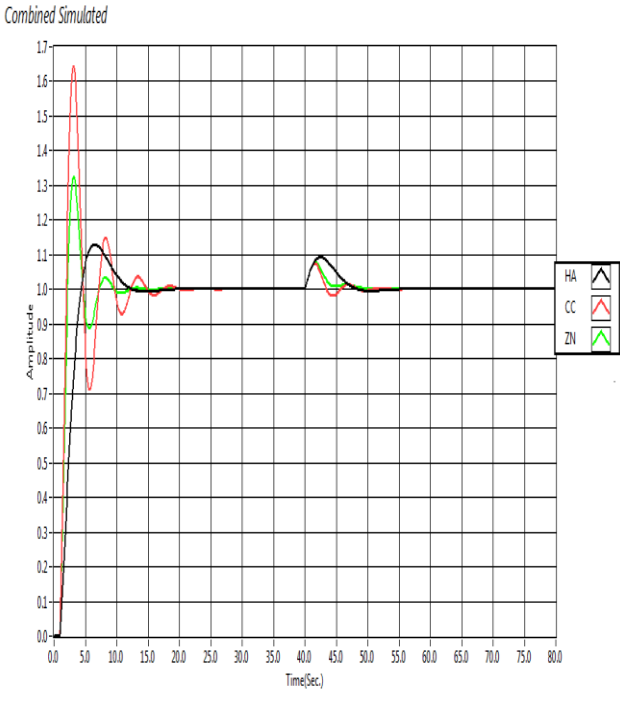

Fig. 5. Step responses of the system with 0.1 step disturbance.

TABLE V. DISTURBANCE RESPONSE PARAMETERS OF THE SYSTEMS

PI Settings	Overshoot (%)	Peak time (s)	Settling Time (s)	Peak Value
Hagglund-Astrom	7	3.82	5.76	1.07
Cohen &Coon	5	2.68	3.44	1.05
Ziegler-Nichols	5	3.05	4.02	1.05

From the results above and considering the system responses to the applied disturbance. It can be seen that the system with the Hagglund-Astrom controller rejects the disturbance with an overshoot of 7%, peak time of 3.82s, peak value of 1.07 and settling time of 5.76s while with the Cohen & Coon controller give disturbance rejection with overshoot of 5%, peak time of 2.68s, peak value of 1.05 and settling time of 3.44s. This portrayed that the Cohen & coon method had outperformed the Hagglund-Astrom and Ziegler-Nichols controllers in this regard.

IV. CONCLUSION

Cohen and Coon and Hagglund-Astrom tuning algorithms for the control of a process plant were successfully implemented and simulated using Labview software with the Ziegler-Nichols method as a base-line design. The respective PI controller settings were calculated based on the different methods of designs and their performances were compared. Results show that the system was stable using the control schemes with the Hagglund-Astrom controller emerging the best even though the Cohen and Coon shows a slightly better disturbance rejection capability.

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