International Journal of Information, Control and Computer Sciences
ISSN: 2517-9942
Vol:7, No:7, 2013

Robust Fractional-Order PI Controller with Ziegler-Nichols Rules

Mazidah Tajjudin, Mohd Hezri Fazalul Rahiman, Norhashim Mohd Arshad, and Ramli Adnan

***Abstract*—**In process control applications, above 90% of the controllers are of PID type. This paper proposed a robust PI controller with fractional-order integrator. The PI parameters were obtained using classical Ziegler-Nichols rules but enhanced with the application of error filter cascaded to the fractional-order PI. The controller was applied on steam temperature process that was described by FOPDT transfer function. The process can be classified as lag dominating process with very small relative dead-time. The proposed control scheme was compared with other PI controller tuned using Ziegler-Nichols and AMIGO rules. Other PI controller with fractional-order integrator known as F-MIGO was also considered. All the controllers were subjected to set point change and load disturbance tests. The performance was measured using Integral of Squared Error (ISE) and Integral of Control Signal (ICO). The proposed controller produced best performance for all the tests with the least ISE index.

***Keywords*—**PID controller, fractional-order PID controller, PI control tuning, steam temperature control, Ziegler-Nichols tuning.

I. Introduction

PID controller is still dominating the feedback control applications until today especially for PI control [1], [2]. In process control applications, more than 90% of the controllers are of PI(D) type [1]. Its application is adequate for wide control problems with modest performance requirements. PI is normally used for a system that can be approximated by a first-order system. Otherwise, PID will be more appropriate. PID control is not suitable for all processes compared to PI which is more universal [3]. Other than system order, the relative dead-time can be used to determine which type of controller to be used. Relative dead-time is a ratio of dead-time and time constant of the open-loop response.

The performance of the closed-loop system mainly depends on the value of P, I, and D gain. The most popular tuning technique is the Ziegler-Nichols that had been proposed since 1942 [4] but was still largely applied in its original form or with some modifications. The rules were simple because not requiring process transfer function. The rules only require information on the process gain, dead-time and lag-time which can be obtained from an s-shaped step response. However, the rule often produced poor robustness since it uses very little information about the plant to be controlled [5]. Ziegler and Nichols presented two methods, a process reaction curve method and frequency response method. The rules were developed based on simulation performed on a large number of different processes to formulate the general PID tuning rules. Modified versions of Ziegler-Nichols were proposed by Cohen-Coon and Chien, Hrones and Reswick [6] where more process parameters were considered.

Later on, Astrom et al. [3] had improvised the Ziegler-Nichols rules using robust loop shaping method. The main idea was to come up with simple rules that are robust to load disturbance. The design looked into maximization of the integral gain with a constraint on maximum load disturbance-to-output sensitivity, Ms. This method was known as M-constrained integral gain optimization (MIGO) that worked very well for PID tuning over wide range of processes [5]. Substantial studies were done over large batch of processes including delay-dominated, lag-dominated, and integrating response which are typically encountered in process control. Based on the outcomes, the tuning rules were drawn by finding relations between the controller parameters and the process parameters. The rules were then known as approximated MIGO (AMIGO).

About a decade ago, the PID controller had been generalized with the implementation of non-integer integral and differentiation proposed by Podlubny in 1999 [7]. The PID was generalized in the form of $PI^{\lambda}D^{\mu}$ involving an integrator of order λ and differentiator of order μ of less than 1. The new structure known as fractional-order PID was acknowledged to improved the performance of the feedback control loop [8]. The concept of fractional-order control (FOC) is represented by fractional-order differential equations. Theoretical framework regarding fractional derivative and integral had been established by Liouville, Riemann, Eular, and Lagrange since the 19th century [9]. The knowledge had been transferred into control engineering by Tustin [10] to control the position of massive object in 1958. This was followed by Manabe [11] around 1960. However, the FOC application was not widely incorporated in control engineering then, due to lack of theory and computational limitation [12].

The interest in fractional-order system has been developed progressively later on. A new control structure known as CRONE controller had been proposed by Oustaloup [13]. CRONE is the acronym for Commande Robuste d'Ordre Non Entier in French which means non-integer robust control. The motivation of CRONE design is to achieve iso-damping (constant phase) characteristics that can tolerate the gain and parameter variations. The improvement of the first-generation

This work was partly supported by UiTM Research fund (600-RMI/DANA 5/3/RIF (660/2012).

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and second-generation CRONE has been made to allow fractional order controller of complex number [14].

The fractional-order PID had been demonstrated by many researchers to give better performance compared to the integer PID. This new technique is proven to provide more flexibility and ability to enhance modeling and control of systems' dynamics [15]. Based on a survey documented by Machado [16], the new development and new possibilities in this area is aggressively discussed. Integer-order approximation for fractional-order system had been investigated since 1960s in other research area such as chemistry and mechanical systems [17]. Some approximation techniques are based on continued fraction expansion (CFE), curve fitting or identification methods and power series expansion (PSE). Oustaloup's Recursive Approximation (ORA) is among the most popular approximation technique. The technique used recursive poles and zeros distribution within specified frequency range to assimilate the frequency response of the fractional-order transfer function.

Recently, more studies had been concentrated on the method for FO-PID tuning [18], [19]. Generally, the design specifications were looking for an infinite gain margin and constant phase margin around the cross-over frequency to obtain robust control towards gain variations [20]. The solutions were then obtained by solving a linear numerical optimization problems as had been reported in [21], [22]. Another tuning approach was by utilizing the Ziegler-Nichols tuning rules based on information of its frequency and step response. The rules were successfully applied by [23] and [24] in their studies. A practical tuning for FO-PI was developed by Yangquan et al. [25] using the same idea proposed in MIGO. They were developing general tuning rules for PI controller with suggested fractional order of the integrator, α. The rules were finalized after comprehensive simulations over various types of processes.

This study demonstrated the application of Ziegler-Nichols tuning rules for IO-PI and extended to the FO-PI. The output performance in steady-state was improved by incorporating an error filter with very small cutoff frequency to increase the system's type. The performance was compared to the IO-PID using AMIGO rules and F-MIGO for the FO-PI. The experimental results from steam temperature control of a distillation plant were provided. This paper is organized in the following order: Section II will explained theoretical development of fractional-order PID and its approximation. Section III discussed on the PID tuning rules proposed by Ziegler-Nichols and the concept of AMIGO and F-MIGO which is the latest development in this area. The steam distillation model is also discussed. Section IV presents the results obtained from the experiments over steam temperature control. Finally, Section V concludes the findings from this study.

II. Fractional-Order PID Controller

Integer-order approximation for fractional-order system had been investigated since 1960s in other research area such as chemistry and mechanical systems [17]. Some approximation techniques are based on continued fraction expansion (CFE), curve fitting or identification methods and power series expansion (PSE). Oustaloup's Recursive Approximation (ORA) is among the most popular approximation technique. The technique used recursive poles and zeros distribution within specified frequency range to assimilate the frequency response of the fractional-order transfer function.

This method is based on the approximation of a function in the form:

$$H(s) = s^m, m \in \Re \tag{1}$$

This function can be approximated by series of rational function synthesized as follows:

$$\hat{\mathbf{H}}(s) = k \prod_{n=1}^{N} \frac{1 + {}^{s}\!/_{\omega_{z,n}}}{1 + {}^{s}\!/_{\omega_{p,n}}} \tag{2}$$

However, the approximation of H(s) is only valid within the boundary of low cut-off and high cut-off frequency defined as [ωl : ωh]. From (2), N represents the number of poles and zeros which has to be selected beforehand. Large value of N permitted good degree of freedom in approximation but increased the computational complexity. On the other hand, small value of N provides less degree of freedom in approximation and resulting appearance of ripple in gain and phase behavior. Proper rules for selecting these parameters were discussed in [26]. The assignment of low and high frequency band limitations could somehow avoid the use of infinite numbers of rational transfer function besides limiting the high frequency gain of the derivative effect [27].

The poles and zeros of the approximated function are calculated using the following recursive equations:

$$\left.\begin{aligned} \omega_{z,1} &= \omega_l \sqrt{\eta} \\ \omega_{p,n} &= \omega_{z,n}\alpha \\ \omega_{z,n+1} &= \omega_{p,n}\eta \end{aligned}\right\}, n = 1 \ldots N \tag{3}$$

where $\alpha = \left(\frac{\omega_h}{\omega_l}\right)^{\mu/N}$ and $\eta = \left(\frac{\omega_h}{\omega_l}\right)^{1-\mu/N}$.

Applications of fractional-order models in control theory had been considered only after two decades. The idea of fractional-order controller was first proposed by Oustaloup through Commande Robuste d'Ordre Non Entier (CRONE which means non-integer robust control) controller in 1991. Later on, Podlubny [7] had initiated the fractional order PID in the form of $PI^{\lambda}D^{\mu}$ in 1999 that involving an integrator of order λ and differentiator of order μ of less than 1. The studies on

International Journal of Information, Control and Computer Sciences
ISSN: 2517-9942
Vol:7, No:7, 2013

PID with fractional power of λ and μ were conducted by many researchers to demonstrate better performance compared to the integer PID. The transfer function of FO-PID is given by

$$C(s) = K_p\left(1 + \frac{1}{T_i s^{\lambda}} + T_d s^{\mu}\right) \tag{4}$$

where K_p, T_i, and T_d are controller gain while λ and μ are the integral and differential power in non-integer number. Fractional PID is the generalization of integer PID such that:

- If λ =1 and μ=1, we obtain a classical PID.
- If λ=1 and μ=0, we obtain a PI controller.
- If λ=0 and μ=1, we obtain a PD controller.
- If λ=0 and μ=0, we obtain a P controller

Hence, if λ and μ were set to arbitrary value between 0 and 1, the controller can be configured to behave within these four possibilities [19], [23], [28].

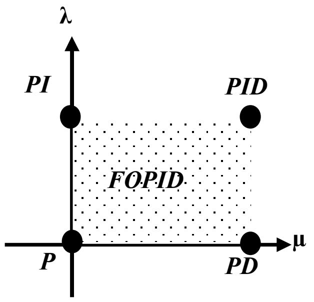


Fig. 1 Fractional PID control space

This is the main advantage of the FO-PID. Other than that, FO-PID was acknowledged by many researchers to provide better control especially to a class of fractal system. Furthermore, FO-PID is less sensitive to changes in process parameters and the controller parameters itself. There were five parameters that can be tuned instead of three as in the conventional version and thus, more design specifications can be achieved from the λ and μ adjustment [18].

The frequency response for differentiator and integrator using ORA was shown in Figs. 2 and 3 respectively. The magnitude and phase of each function related to fractional power λ is given by,

$$\left.\begin{aligned} 20\log\left|\hat{s}^m\big|_{s=j\omega}\right| &= 20m\log(\omega)dB \\ \angle\hat{s}^m\big|_{s=j\omega} &= \frac{\pi m}{2} \end{aligned}\right\}\omega_l \le \omega \le \omega_h \tag{5}$$

where m represents the magnitude of λ and μ and will be used throughout this paper. The gain and phase can be adjusted between ±20 dB/dec and ±90º. This characteristic enable for more accurate design of the PID controller.

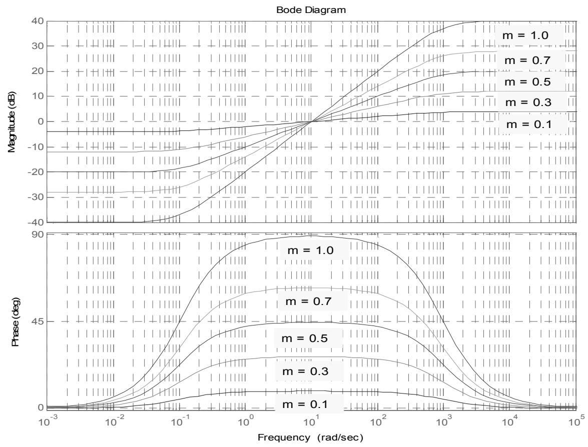


Fig. 2 Bode diagram of ORA on s^m

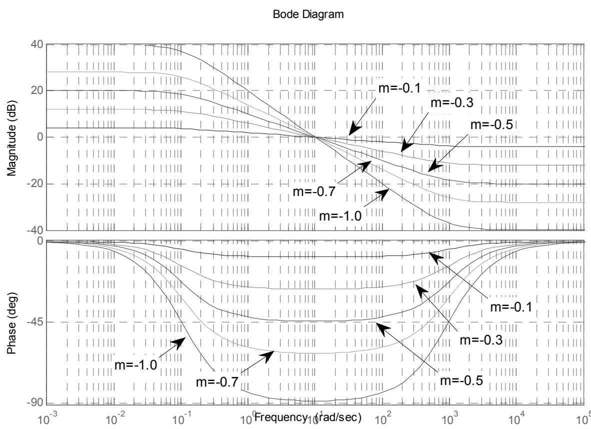


Fig. 3 Bode diagram of ORA on s^{-m}

III. PID Tuning Rules

The controller design was applied to steam temperature control system which exhibit non-linear properties over the whole range. But, in this study, the operating range was limited from 80°C - 100°C where the output response is closely approximated with FOPDT system with s-shaped step response. This section explains the PI tuning rules outlined by Ziegler-Nichols, AMIGO, and F-MIGO for FO-PI. The proposed method of error filter with adjustable n was also explained and proved to provide good performance even though with Z-N tuning rules for the PI controller.

A. Ziegler-Nichols (Reaction Curve Method)

This study applied Ziegler-Nichols PID tuning based on a process reaction curve. It should be noted that, these rules were only accurate for a process with an s-shaped step response or otherwise will not produce satisfactory response. The PID parameters can be acquired from the step response test and no process model is required. The tuning rules are given by (6) and (7).

$$K = \left(\frac{0.9}{K_p}\right)\left(\frac{T}{L}\right) \tag{6}$$

$$T_i = 3.3L \tag{7}$$

Information about the process gain (Kp), process dead-time, L and process time constant, T can be obtained from the process reaction curve. These parameters are described in Fig. 4.

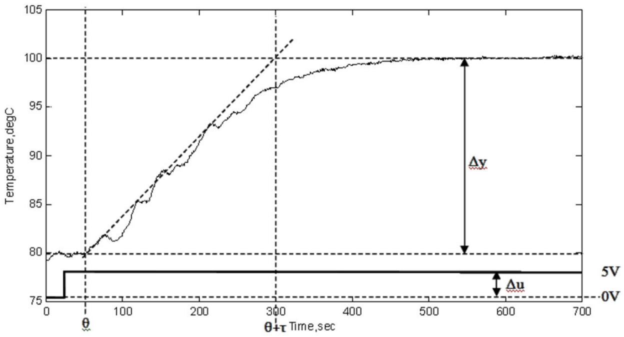


Fig. 4 Process reaction curve of steam temperature in hydro-steam distillation process

The controller parameters are then calculated according to the rules given in (6) and (7) for Kp=4.5, L=25sec, and T=280 sec. This information creates an FOPDT system as follows:

$$G(s) = \frac{4.5}{280s+1}e^{-25s} \tag{8}$$

For the standard PID structure, the following PI controller was obtained:

$$C(s) = 2.19\left(1 + \frac{1}{82.5s}\right) \tag{9}$$

B. FO-PI (Z-N) with Error Filter

In order to improve the overall closed-loop response, this study proposed an FO-PI controller with the P and I obtained from the Ziegler-Nichols rules given above. Based on simulation over a case study of an FOPDT-type system, the PI performance can be improved a lot with fractional power of I.

Simulation was done for λ = -0.1,-0.5, and -0.9. A general observation made was that the FO-PI produced a significant steady-state error even though it can improve the overshoot of the response. This is due to the absence of pole at the origin when the integrator of fractional-order was approximated using ORA method. This issue had been discussed in [12], [21], [29] with proposals on how to minimized the error.

After some simulation studies, the error filter proposed by Feliu-Batlle et al. [21] was considered. The original error filter is in the following form:

$$G_e(s) = \frac{s+n}{s} \tag{10}$$

where n being a small value so that high frequency specifications were maintained and the system gain will not altered drastically. This approach was applied in this research for steady-state error compensation but with some modifications.

The effect of the error filter can be described through Bode plots of the integrator terms and the composite PI controller given in Fig. 5. The frequency response was for λ=-0.5. From the figure, the error filter just increased the system's type and maintains all other behaviors around specified frequency range. The overall magnitude specifications can be achieved by a simple gain adjustment.

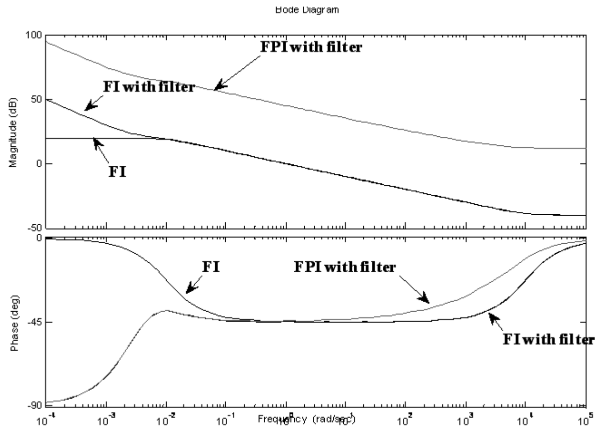


Fig. 5 Bode plot of F-PI with error filter when λ= -0.5

This study proposed a modification such that the value of n is adjustable with respect to λ. The movement of zero has significant impact on the phase margin. For λ=0.9, great improvement in %OS was observed when n=0.003 compared to n= 0.03. The summary was presented in Table II with best performance was obtained when λ=0.1 and n=0.03. This setting will be demonstrated with experiment in Result and Discussion section.

TABLE II
EFFECT OF CUT-OFF FREQUENCY OF ERROR FILTER

λ	k	n	Settling time (s)	OS (%)	Steady-state error (ºC)
-0.1	0.79	0.3	239	46.93	0
-0.1	0.79	0.03	-	30.07	0.84
-0.5	0.32	0.03	224	40.00	0
-0.9	0.1	0.03	294	65.47	0
-0.9	0.1	0.003	301	50.07	0

C. PI-AMIGO

This rule was proposed by Astrom and Hagglund in [3], [30]. They tried to improve the basic rules given by Ziegler and Nichols by introducing a classification index of relative dead-time, τ. τ is an essential parameter that can better described the type of processes and is highly influencing the controller performance. τ was defined as:

$$\tau = \frac{L}{L+T} \tag{11}$$

where L and T is the dead-time and lag- time respectively.

Each process can be classified as delay dominated when $\tau>0.5$, lag dominated when $\tau < 0.5$ and balanced system when $\tau = 0.5$. The controller parameters were determined from a test batch including over 134 different processes based on correlation with relative dead-time, τ of the process. The PI-AMIGO tuning rules were given by (12) and (13) [31]:

$$K = \frac{0.15}{K_p} + \left(0.35 - \frac{LT}{(L+T)^2}\right)\frac{T}{K_p L} \tag{12}$$

$$T_i = 0.35L + \frac{13LT^2}{T^2 + 12LT + 7L^2} \tag{13}$$

D. F-MIGO

F-MIGO is an extension of MIGO applied for a fractional-order PI^{λ} for normal first-order system (FOPDT). This rule was designed by Yang Quan et al. [25] to accommodate the design of FO-PI controller which include the determination of λ. The tuning rules also considering the relationship between normalized controller parameters and the relative dead-time, τ. Based on evaluation to numbers of FOPDT process models with different τ, the F-MIGO proposed the following rules with respect to τ:

$$\lambda = \begin{cases} 1.1 & if \quad \tau \geq 0.6 \\ 1.0 & if \quad 0.4 \leq \tau < 0.6 \\ 0.9 & if \quad 0.1 \leq \tau < 0.4 \\ 0.7 & if \quad \tau < 0.1 \end{cases} \tag{14}$$

$$K = \frac{1}{K_p}\left(\frac{0.2978}{\tau + 0.000307}\right) \tag{15}$$

$$T_i = T\left(\frac{0.8578}{\tau^2 - 3.402\tau + 2.405}\right) \tag{16}$$

where λ is the fractional-order, τ is the relative dead-time, K_p is the process gain, T is the time constant, K is the proportional gain, and T_i is the integral time constant. By determining τ, the value of λ, K, and T_i can be calculated using (14)-(16). Their study suggested that a system with very small dead-time may not require full integrator to give good closed-loop performance.

IV. Results and Discussions

This section provides experimental results of the PI together with FO-PI that were tuned using the methods previously discussed. The fractional integrator was approximated using ORA with N = 4, ωL=0.01 rad/s and ωH=10000 rad/s. The approximate transfer function was multiplied with gain, k so that the Bode magnitude crossed 0 dB (unity gain) at 1 rad/s. All the controller settings are summarized in Table III where m is the fractional-order, k is the gain to reset the fractional integrator to 0dB, and n is the cut-off frequency of the error filter. The study was conducted on steam temperature process described by (8) with τ = 0.08 (lag dominating process). Ziegler-Nichols rules proposed large gain whereas, the rules based on MIGO maximizing the integral time of almost twice from the Ziegler-Nichols.

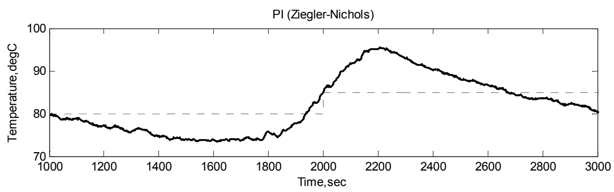
TABLE III
Controller Settings

#	Controller	K	Ti	λ	k	n
1	PI (Z-N)	2.19	82.5			
2	PI-AMIGO	0.7	161.53			
3	F-MIGO	0.82	112.28	-0.7	0.19	
4	FO-PI (Z-N) with filter	2.19	82.5	-0.1	0.79	0.03

A. Set Point Change

The control performance was evaluated during set point change and load disturbance test. The set point was changed from 80°C to 85°C with no changes in other parameter. The performance was compared using Integral of Squared Error (ISE) and Integral of Control Error (ICO) for both cases.

Fig. 6 shows step change response by PI (Z-N). The closed-loop response did not follow the given set point and keep oscillating without damping. The control signal acting in an ON/OFF manner as the controller gain is high and the control signal was constrained by the 0 to 5 volt voltage. Furthermore, the system fails to respond immediately to the control signal since the lag time is very large (280 sec). This result shows the incompetency of the Z-N tuning rules to be applied directly on every type of process.



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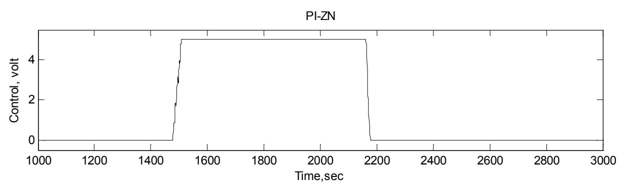
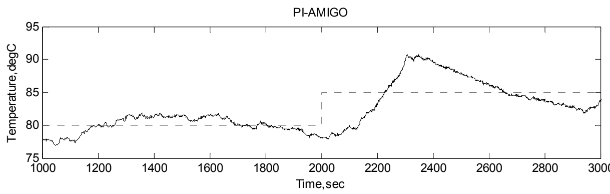


(b)

Fig. 6 PI-ZN set point change (a) temperature (b) control volt

International Journal of Information, Control and Computer Sciences
ISSN: 2517-9942
Vol:7, No:7, 2013

Fig. 7 shows a modified version of Z-N rules by considering the effect of dead-time and lag in the tuning rules. The response produced by PI-AMIGO shows better performance with the ability in tracking the set point but it still producing high overshoot.



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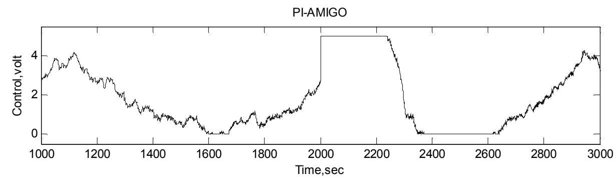
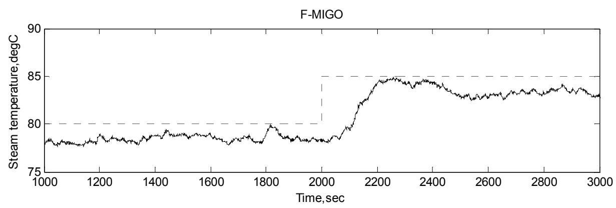


(b)

Fig. 7 PI-AMIGO set point change (a) temperature, (b) control volt

The closed-loop performance was improved by introducing a fractional term in the integrator. But as discussed earlier, the approximation causes significant error during steady-state but the overshoot was noticeably reduced. This result agrees with Yang Quan et al. that lag dominating process did not require a full integrating controller.



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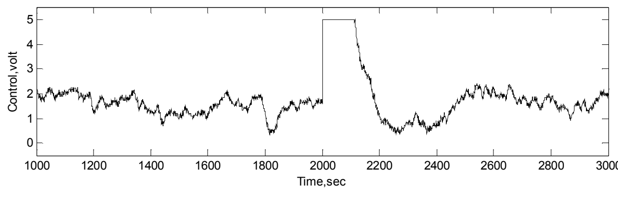
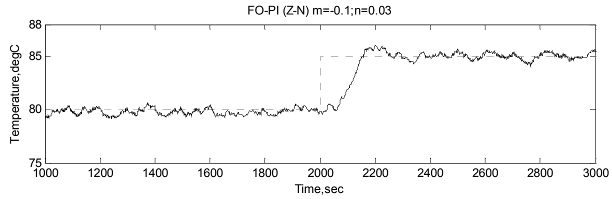


(b)

Fig. 8 F-MIGO set point change (a) temperature, (b) control volt

Fig. 9 shows the output response using the proposed technique. The steady-state error was eliminated by the error filter and the response was faster with negligible overshoot. The fractional order was much smaller (0.1) than the proposed value (0.7) for system with very small dead-time (< 0.1). But, what happens if smaller order is used? This result shows that smaller order produced a better response for a system with smaller τ. And, the results also proved that the Z-N tuning rules were applicable to the FO-PI controller setup where the performance can be improved with the fractional order integrator with some modifications.



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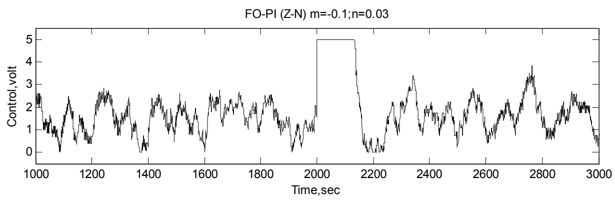
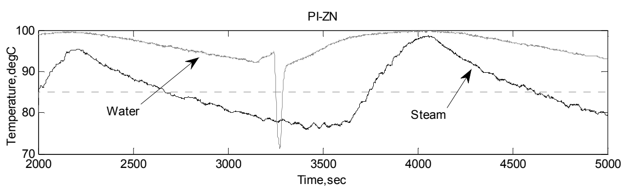


(b)

Fig. 9 FO-PI with error filter set point change (a) temperature, (b) control volt

B. Load Disturbance

Load disturbance rejection is also important to evaluate the controller's robustness. In this case, the disturbance was introduced by increasing the water volume by 1 liter. This will reduce the water temperature and hence, the steam temperature it generates. PI-ZN controller was oscillating and did not response to the changes. PI-AMIGO can reject the disturbance with sluggish response in the beginning.



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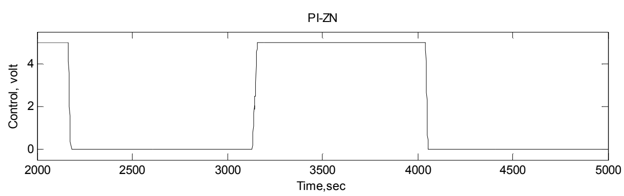

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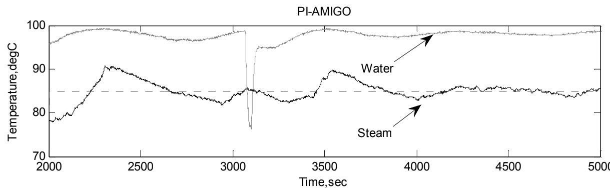
Fig. 10 PI-ZN load disturbance response (a) temperature, (b) control volt



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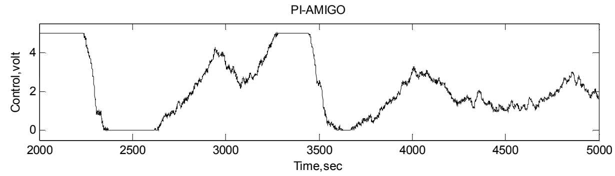
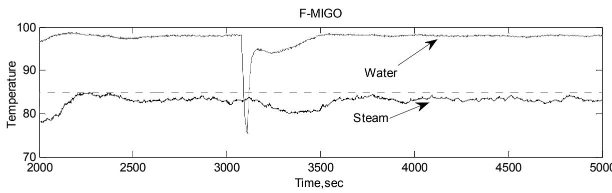


(b)

Fig. 11 PI- AMIGO load disturbance response (a) temperature, (b) control volt

F-MIGO controller shows iso-damping property but still produces steady-state error. The best output response was observed in the proposed controller as shown in Fig. 13.



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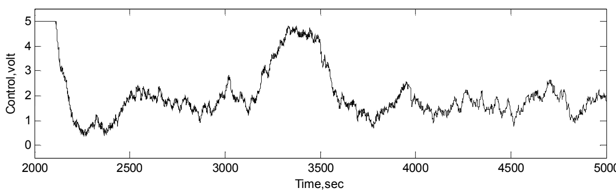

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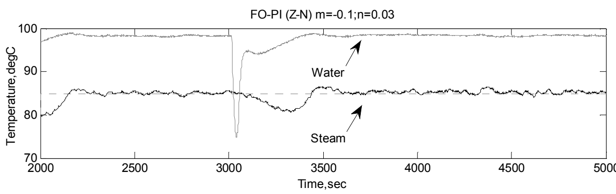
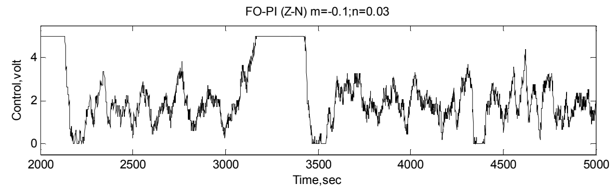
Fig. 12 F-MIGO load disturbance response (a) temperature, (b) control volt



(a)



(b)

Fig. 13 FO-PI with error filter load disturbance response (a) temperature, (b) control volt

The overall performance of each controller can be measured from their performance index of error (ISE) and the efficiency of the controller output. The data was listed in Table IV and the best performance was shaded. During set point change, controller #4 gave best output in terms of less error index but controller #3 produce less control effort. The performance was the same during load disturbance test. These results can be validated by comparing Figs. 12 and 13. F-MIGO gave smoother control but it compromising the output response. On the other hand, FO-PI with the error filter has higher P gain for more aggressive control effort but better output performance.

TABLE IV
CONTROLLER PERFORMANCE INDICES

#	Controller	Set point change		Load disturbance	
		ISE(x10^4)	ICO	ISE(x10^4)	ICO
1	PI-ZN	4.765	3382	12.34	5365
2	PI-AMIGO	1.338	3784	1.639	6543
3	F-MIGO	0.951	3517	1.806	6178
4	FO-PI (ZN) with error filter	0.254	3552	0.5671	6610

V. CONCLUSIONS

This study compares three PI controllers that tuned using Ziegler-Nichols, AMIGO and F-MIGO with the proposed FO-PI tuned with Ziegler-Nichols but was cascaded with an error filter to eliminate steady-state error. All the controllers were evaluated experimentally to a steam temperature process which is of FOPDT type with very small τ. The evaluation includes robustness against set point change and load disturbance test. The evaluation was made in terms of ISE and ICO for output and controller efficiency. In general, the proposed controller shows best performance but it demands higher control effort as compared to F-MIGO that measured by ICO index.

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