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INTEGRATION FRACTIONAL PID ON SISO SMISD PLANT IN NOISY SYSTEM

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ABSTRACT

This study compares various type of Fractional order PID (FOPID) Controller in regulating the steam temperature in distillation tank in the Small-Medium Industry Steam Distillation (SMISD) with intention to improve the tracking performances due to presence of noise. Three types of new modification version of FOPID have been proposed here. Based on literature review shows that the pole in origin of FOPID are absent due approximation by using Oustaloup Algorithm (ORA). The overall performances can be elevated by integrating the error filter. This new controller are named FOPIDer. Another problem faced during the development of FOPID is the effect of noise especially on derivative term. The sensitivity of derivate term are increasing exponentially as well as the effect of noise which are always uneven and random signal. Hence, to alter the effect of noise, the low pass filter are added to FOPID. By doing so, the effect of noise are gradually decreased and this controller are named as FOPIDlp. Both feature of error filter and low pass filter are integrate into single FOPID controller namely FOPIDerlp. Comparisons of assessing the effectiveness of controller performance and analyzed are based on the mean-square error (MSE) criteria index in noisy environment. This criteria measures the deviation of steam output from the predetermined set point which is 85 degree Celsius in this case. The real time showed that the FOPIDerlp provide the best performance in providing smaller MSE.

Keywords: FOPID controller, error filter, low pass filter.

INTRODUCTION

The PID controller is an essential part in the feedback control loop in the industry application (McMillan, 1983), particularly at the lowest level (Yun, Kiam Heong, & Chong, 2006). Since the introduction of PID control in 1910, the popularity has grown exponentially due to its easy understanding. The success and longevity of PID controller is due to its control structure based on the classical control theory which is simple easiness in tuning and reliable, yet it delivers adequate solution for wide control problem (Mazidah Tajjudin, Rahiman, Arshad, & Adnan, 2013).

The PID controller structure involves three-term functionality covering the treatment to both transient and steady-state responses which is the proportional, the integral and the derivative values denoted as *P*, *I*, and *D* respectively (Marzaki, Jalil, Md Shariff, Adnan, and Rahiman, 2014). The performances of PID are closely related on how its value are tuned. Many famous and far-reaching methods can be found in the literature, such as the Ziegler-Nichols (Ziegler & Nichols, 1942) and Cohen-Coon method (Cohen & Coon, 1953). Both tuning rules are relatively simple because it only requires the dead-time, process gain and lag-time which were obtained from open-loop responses (M. Tajjudin, Tahir, Rahiman, Arshad, & Adnan, 2013). In Ziegler-Nichols method, the output of the system is analyzed, and then based on the shape of the output, the PID parameters are given directly according to a set of clear relationships, while in Cohen-Coon method where the main design criteria focusing on load disturbance rejection. After the Ziegler-Nichols and Cohen-Coon method, many farfetched design methods were preponed.

Until the preceding year, fractional-order calculus (FOC) was considered as theoretical only due to oblivion in the inherent complexity and lack of an accepted geometric and physical interpretation (Cafagna, 2007). However, the increasing computation calculation capability enabled the scientists to solve complex FOC calculation (Cafagna, 2007). Podlubny in 1999 rejuvenated the FOC area by suggested convincing both geometric interpretation of Riemann-Liouville and physical interpretation for Riemann-Liouville (and Caputo) fractional differentiation (Podlubny, 1999a). Several researches have been conducted with the aim of improving the performance of the PID.

The fractional-order system has been designed to reduce the backlash suspension vibration for torsional system. They proposed the PIDK controller instead of the traditional PID controller. The nonlinear that occurred in gear backlash causes the vibration in the system (Ma & Hori, 2003). The traditional PID was unable to cater such problem. On the other hand, the additional degree of freedom in PIDK controller enable direct tuning value of *K* that is related to the frequency responses of the system. Thus, this lead to a more straightforward designs and tunings. The other effort done by Oustaloup had developed the Commande Robuste d'Ordre Non Entier (CRONE) (Lanusse, Oustaloup, & Mathieu, 1993; Oustaloup & Bansard, 1993; Oustaloup, Mathieu, & Lanusse, 1993). He has successfully applied CRONE to various system such as car suspension, which have a constant phase characteristic that enable it to tolerate to various gain and parameter variations.

The better understanding of fractional calculus has led to design of Fractional-order PID (FOPID)

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controller. The basic idea behind FOPID is to extend the PID from integral order to non-integer order (Sadati, Ghaffarkhah, and Ostadabbas, 2008) by modifying the traditional PID controller by introducing the non-integer integral and differentiator. By doing so, more parameters can be tuned for instance of three parameters K_P, K_I, K_D but also addition two parameter λ and μ. This grant more flexibility and robustness to the system. Fractional order systems have high degree of flexibility to imitate the non-linearity systems and high order system, yet using less coefficient than integral order systems. This marks the beginning of a new PID structure named as fractional-order PID (FOPID). This progressing work was inspired by Podlubny in (Podlubny, 1999b). In his work, he proposed that the generalization of form $PI^{\lambda}D^{\mu}$ where λ and μ represents the real non-integer power for both integral and derivative term respectively.

FRACTIONAL-ORDER CALCULUS

Basic theory of fractional-order calculus

Fractional Calculus is a mathematical subject which can be traced back to 300-year old ago (Jun-yi, Jin, & Bing-Gang, 2005). Basically, the idea behind the fractional calculus is to generalize the classical integral order calculus to non-integer order operator (Tepljakov, Petlenkov, Belikov, & Finajev, 2013). The real order generalize is presented as in equation (1):

$$aD_t^{\alpha} = \begin{cases} \frac{d^{\alpha}}{dt^{\alpha}} \\ 1 \\ \int_a^t (d\tau)^{-\alpha} \end{cases} \tag{1}$$

Where a and t denotes the limit of the operation and α denotes the fractional order.

There are several definition of fractional order calculus that had been published. Some common definition such as Riemann-Liouville, Grunwald-Letnikov and Caputo definition as describe in equation (2-6).

A. Riemann-Liouville

Fractional Integral:

$$J_c^{\alpha} f(t) = \frac{1}{\Gamma(\alpha)} \int_c^t \frac{f(\tau)}{(t-\tau)^{1-\alpha}} d\tau \tag{2}$$

Fractional Derivative:

$$D^{\alpha} J^{m-\alpha} f(t) \tag{3}$$

B. Grunwald-Letnikov
Fractional Integral:

$$D^{-\alpha} f(t) = \lim_{h\to 0} h^{\alpha} \sum_{m=0}^{\frac{t-a}{h}} \frac{\Gamma(\alpha+m)}{m!\Gamma(\alpha)} f(t-mh) \tag{4}$$

Fractional Derivative:

$$D^{\alpha} f(t) = \lim_{h\to 0} h^{\alpha} \frac{1}{h^{\alpha}} \sum_{m=0}^{\frac{t-a}{h}} (-1)^m \; x \; \frac{\Gamma(\alpha+1)}{m!\Gamma(\alpha-m+1)} f(t-mh) \tag{5}$$

C. Caputo
Fractional Derivative:

$$D^{\alpha} f(t) = J^{m-\alpha} D^m f(t) \tag{6}$$

The choices of suitable definition or another, depending on the application and the preference of the designer. For example Caputo definition is suitable if real physical application is considered such as system identification and biochemistry area. Grunwald-Letnikov definition is suitable for numerical evaluation while Riemann- Liouville definition is used to find the analytical solution of simple function.

Fractional order systems have high degree of flexibility to imitate the non-linearity systems and high order system, yet using less coefficient than integral order systems. Using the definition above such as Riemann-Liouville, Grunwald-Letnikov, Caputo, and Cauchy for modelling purposed rise no difficulty. However, implementation on real-time applications are significantly difficult because it required all history of the function and local condition of evaluation time to be integrated.

Approximation are required to enable the Fractional-order system (FOS) to run in real-time application. In practice, FOS can be approximated into linear high order system while maintaining the constant phase with chosen frequency band. There are three types of classification to approximate FOS which are computation method based on analytic equation, discrete time approximation technique and continuous time approximation technique.

However, this paper are focusing on approximation of the fractional system using rational function in continuous time. One of the most popular technique in approximation FOS in continuous time is the Oustaloup's Recursive Approximation (ORA) method. This technique is originally invented by Alan Oustaloup as one of the sub part of Commande Robuste d'Ordre Non Entier (CRONE) controller. The CRONE framework are based on the principle that ensuring the constant phase (ISO-damping) characteristics while subject to various gain and parameter variations. The CRONE itself had gradually evolved into three generation; first generation CRONE (Oustaloup & Bansard, 1993), second generation CRONE (Oustaloup *et al*., 1993) and the third generation CRONE (Lanusse *et al*., 1993). The evolution of CRONEs from the first and second generation have allowed fractional order controller of complex number (Mazidah Tajjudin *et al*., 2013)

Parameters of fractional-order PID controller

Fractional-order system (FOS) require its algorithm to approximate which enable it to run in real-time application. In practice, FOS can be approximated into linear high order system while maintaining constant phase with the chosen frequency band. The integral-order approximation for FOS have been carried out since 1960s in chemistry and mechanical systems. The main focus of this study are the approximation in continuous time and

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one of the popular filter in it is the Oustaloup's Recursive Approximation (ORA) method. Among all available filters, ORA has a very good fitting to the fractional-order differentiator (Xue, Chen, and Atherton, 2008). This method is trying to imitate the frequency response of fractional-order transfer function by using recursive zero and pole distribution within specific frequency range.

Assuming expected fitting range is (ω_l, ω_h) representing low cut-off frequency and high cut-off frequency respectively. Then, approximation ORA can be written in equation (7):

$$G_f(s) = K \prod_{k=-N}^{N} \frac{s+w'_k}{s+w_k} \tag{7}$$

Where the poles, zeros and gain of filter can be recursively evaluated as:

$$w'_k = \omega_b \left(\frac{\omega_h}{\omega_l}\right)^{\frac{k+N+\frac{1}{2}(1-\gamma)}{2N+1}}$$

$$w_k = \omega_l \left(\frac{\omega_h}{\omega_l}\right)^{\frac{k+N+\frac{1}{2}(1+\gamma)}{2N+1}}$$

$$K = \omega_h^{\gamma}$$

where γ is the order of differentiation, *2N+1* is the order of the filter.

General structure of FOPID controller

The differential equation of FOPID as described in equation (8):

$$u(t) = K_p e(t) + \frac{K_p}{T_i} D_t^{-\lambda} e(t) + K_p T_d D_t^{\mu} e(t) \tag{8}$$

By using Laplace transformation in equation (8), the continuous form of FOPID is obtained as shown in equation (9):

$$G_c(s) = K_p + \frac{K_p}{T_i} s^{-\lambda} + K_p T_d s^{\mu} \tag{9}$$

It is obvious that the structure of FOPID have more parameters compared to the conventional PID structure. This means that more parameters can be tuned instead of only three parameters K_P, K_I, K_D but also in additional two parameters, λ and μ. These expression provide more flexibility and robustness to the system. Hence, it is less sensitive to process parameters variation. The fractional PID resembled several control structures such as P, PI, PD and PID as shown in Figure-1. The summary of FOPID is shown as below:

When $\lambda = 0$ and μ=0, it become P Controller.
When $\lambda = 1$ and μ=0, it become PI Controller.
When $\lambda = 0$ and μ=1, it become PD Controller.
When $\lambda = 1$and μ=1, it become PID Controller.

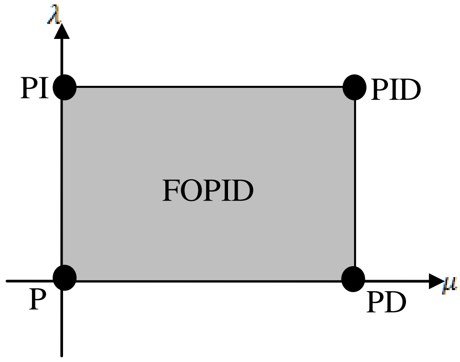

Figure-1. General structure of FOPID.

Controller design

The fractional-order controller are operated based on the integral and differentiator that had been approximated using the ORA algorithm which only valid between the frequency of interest only. The previous study shows that on Small-Medium Industry Steam Distillation (SMISD) plant is operated in low frequency (Mazidah Tajjudin *et al.*, 2013). Based on this argument, the selected range of frequency of interest between 0.01 rad/s to 10000 rad/s to represent the fractional-order PID coefficient w_l and w_h respectively.

Before the experiment can be executed, the value of *N* must be selected. The value of *N* represents the number of pole and zero for both integral and differentiator. Below, Figure-2 and Figure-3 are showing the illustrated effect of both integral and differentiator respectively.

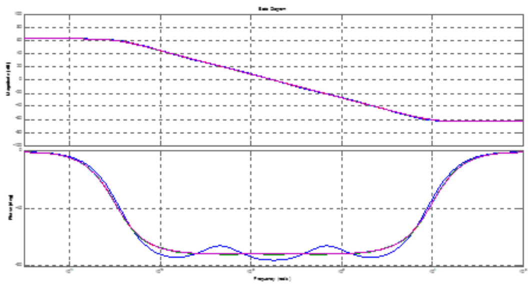

Figure-2a. Full scale figure effect of value N for integrator term.

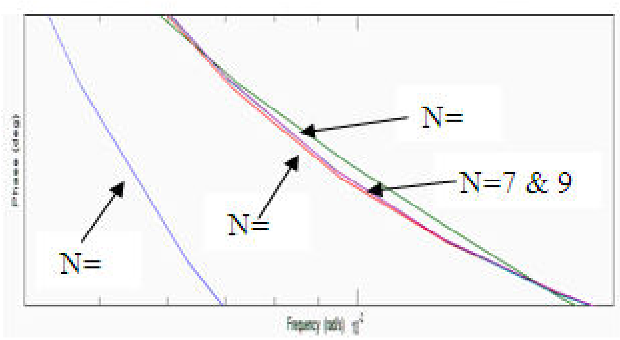

Figure-2b. Magnification scale figure effect of value *N* for integrator term.

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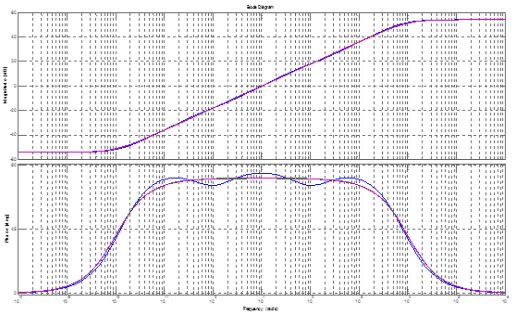

Figure-3a. Full scale figure effect of value *N* for Differentiator term.

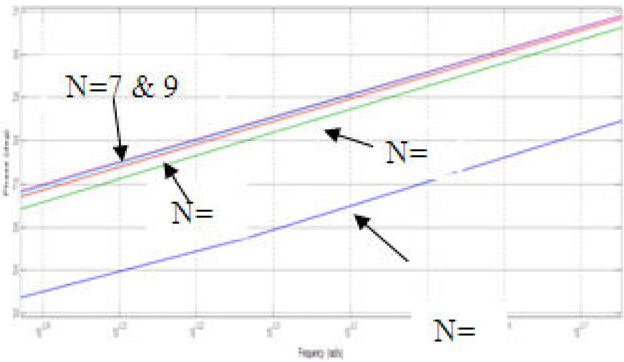

Figure-3b. Magnification scale figure effect of value *N* for differentiator term.

Figure-2a and Figure-2b show that *N*=1 and *N*=3 shows some ripple in its phase response. Further magnification shows *N*=5, showing slight ripple although it is not obvious. For *N*=7 and *N*=9, no significant difference are observed in the shape. The same observation are also noticed for differentiator in Figure-3a and Figure-3b where the only difference is the slope for magnitude. Although the large value of *N* allows good approximation, however it requires high computation effort. Some consideration between good approximation and computation effort must be determined. Based on this result, *N*=7 is chosen to represent both the integrator and differentiator for our system.

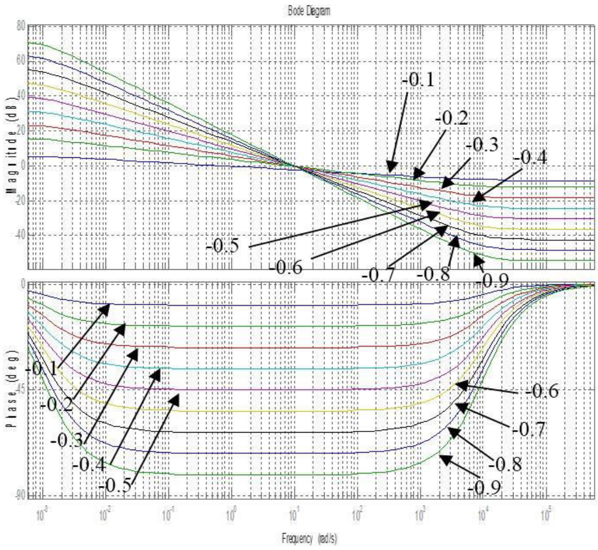

Figure-4a. Bode plot of *M* before gain, *G* for integrator term.

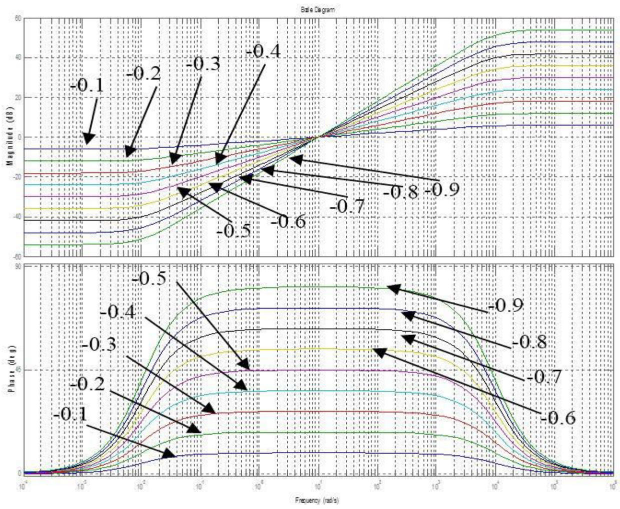

Figure-4b. Bode plot of *M* after gain, *G* for integrator term.

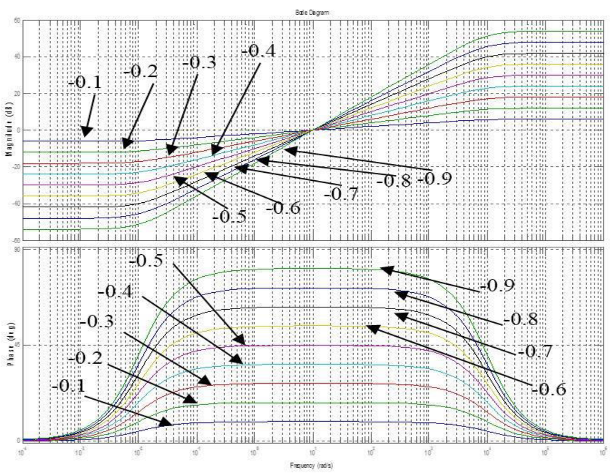

Figure-5. Bode plot for differentiator term.

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After that, a sequence of systematic simulation by using SIMULINK MATLAB software had been carried out to replicate the actual system, behavior in real time. The purpose of this simulation is to determine the optimal value of *M*, where it represents the magnitude of λ and μ. To achieve better transient response gain and magnitude are adjusted between ±20db/decade and ±90 degree with respect to *M* by adjusting the gain, *G* (M. Tajjudin *et al.*, 2013) as shown in Figure-4a and Figure-4b. However, for Figure-5, it does not requires any adjustment as it is already optimal. The full description of Small-Medium Industry Steam Distillation Plant (SMISD) is shown in (Marzaki *et al.*, 2014; Marzaki, Tajjudin, Adnan, Rahiman, and Jalil, 2013).

Table-1. Results of simulation of λ=-0.9 and 0.1<μ<0.9.

λ	μ	Gain (μ)	Steam temperature	Steady state error
-0.9	0.1	0.89	85.01	0.006095
	0.2	1.25	85.09	0.08603
	0.3	1.39	85.45	0.4521
	0.4	1.59	86.95	1.951
	0.5	1.79	93.33	8.331
	0.6	2.00	128.2	43.22
	0.7	2.24	167.6	82.59
	0.8	2.52	167.6	82.59
	0.9	2.85	167.6	82.59

*Shaded box represented the best response

Table-1 above shows the results tabulated from the simulation. The actual number of simulation that have been done are 99 simulation which consist of combination of -0.1 to -0.9 for λ and 0.1 to 0.9 for μ. However, due to space constrain, we only show λ=-0.9 and it μ combination.

Error filter

The overall closed loop performance of system can be improved significantly by integrating error filter in the proposed FOPID controller. This idea is based on the paper proposed by V. Feliu-Batlle in (Feliu-Batlle, Pérez, & Rodríguez, 2007) where the error filter are tested on system based on canals irrigation. The form of error filter are shown as in equation (10). By integrating the error filter in to the system, significantly the steady-state error and overshoot of the response can be improved (Mazidah Tajjudin *et al.*, 2013).

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

The value of *n* are selected arbitrary small, thus system characteristics of high frequency specification are maintain and does not effect on system gain.

Therefore, the new modification fractional integrator term is shown in equation (11):

Before modification, $\frac{K_p}{T_i}s^{-\lambda}\rightarrow$

After medification, $\frac{K_p}{T_i}s^{-\lambda}\frac{s+n}{s}$ (11)

Low Pass Filter in Derivative Term

In simulation test, the proposed FOPID controller with error filter runs smoothly without any problems. However, different situation are observed in the real time application. Things are not going well as predicted in simulation case. One of the factor that contributes to this problem is the measurement noise that came from the sensor. To overcome this problem, some minor modifications were done to fractional derivative term by integrated low pass filter to reduce the effect of high frequency signal (Leva and Maggio, 2011). Therefore, the modification is shown by equation (12). Note that, the suggested value of *N* was selected to be in the range of 2≤*N*≤20 (Marzaki *et al.*, 2014).

Before the modification, $K_pT_ds^{\mu}\rightarrow$

After the modification, $K_p\frac{T_ds^{\mu}}{\left(\frac{T_d}{N}\right)s^{\mu+1}}$ (12)

The realization of FOPID controller with error filter and low pass filter is shown in equation (13):

$$G_c(s) = K_p + \frac{K_p}{T_i}s^{-\lambda}\frac{s+n}{s} + K_p\frac{T_ds^{\mu}}{\left(\frac{T_d}{N}\right)s^{\mu+1}} \tag{13}$$

RESULT AND DISCUSSIONS

In order to evaluate the practical utility of the proposed FOPID controller, a series of real-time implementation have been conducted. The real-time experiment was carried out on the Small-Medium Industry Steam Distillation Plant (SMISD). Results of the simulation are not discussed here due to space constrain. There are several controllers that were tested here such as FOPID controller, FOPID Controller with error filter

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(FOPIDer), FOPID Controller with low pass filter (FOPIDlp) and lastly FOPID Controller with combination error and low pass filter (FOPIDerlp). Throughout the experiments, the initial temperature of SMISD was set to be at 30 degree Celsius. All controllers were tested for set point change at 85 degree Celsius and performance analysis are done by using MSE criterion.

Result shows the responses of regulating steam temperature that were controlled by Fractional order PID Controller. The algorithm of Fractional order PID Controller were approximated by using the Oustaloup's Recursive Approximation (ORA) method. This method was used to approximate the integrator and derivative term. The results above show that there is no visible steady state value of steam temperature due to the presence of measurement noise in the system. There are many factors influencing the measure noise on the system such as the noises from the RTD sensor and nature of steam. The slightly variation of resistance change in RTD causes inaccurate measurement where the manufacture of RTD state that the accuracy is within ± 0.15 degree Celsius. In addition, the nature of the steam itself where it is volatile and nonlinear in nature causes noise in measurement. For this real-time experiment, we found out that integrator term optimal value is at 0.9 and derivative at 0.1. This value was selected after countless trials in the simulation. Figure-6, Figure-7, Figure-8 and Figure-9 shows responses of FOPID controller, FOPIDer Controller, FOPIDlp and lastly FOPIDerlp respectively as a response of step change test. Each figure consists of response of system in steady state condition for duration 10000 second (t=15001 second to t=25000second). The analysis results based on MSE were tabulated in Table-2.

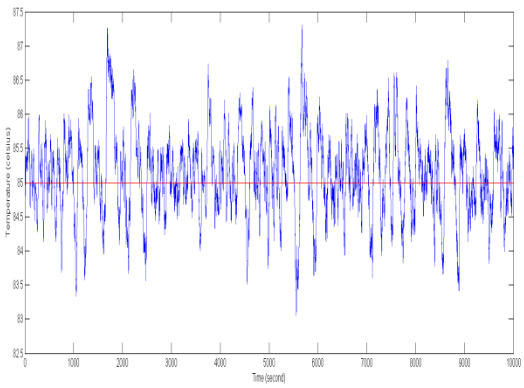

Figure-6. Steady state response of 85 degree celsius of FOPID controller.

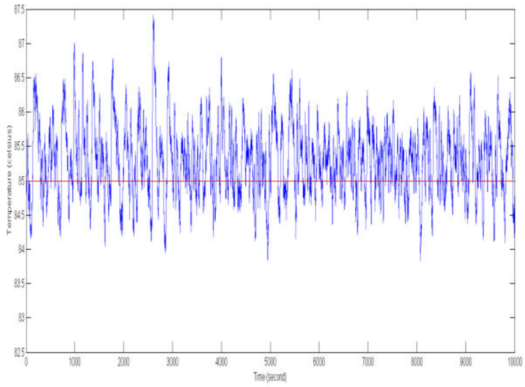

Figure-7. Steady state response of 85 degree celsius of FOPIDer controller.

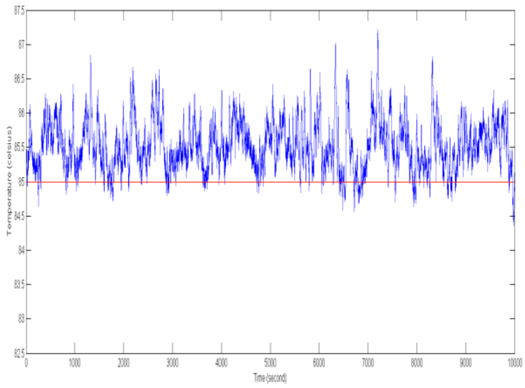

Figure-8. Steady state response of 85 degree celsius of FOPIDlp controller.

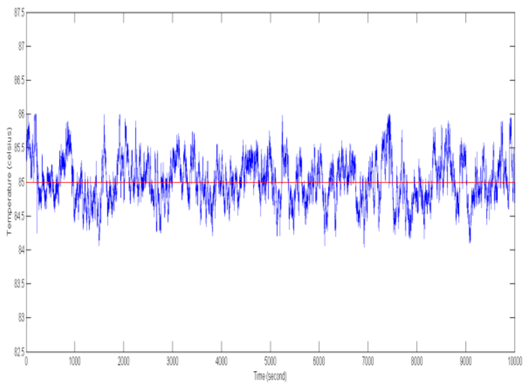

Figure-9. Steady state response of 85 degree celsius of FOPIDerlp controller.

Table-2. Result performance of various FOPID controller.

Controller	MSE	Max Oscillation	Min Oscillation
FOPID	0.4031	87.3065	83.0584
FOPIDer	0.3584	87.4100	83.8366
FOPIDlp	0.4146	87.2149	84.3585
FOPIDerlp	0.1163	85.9987	84.0338

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Based on the visual observation on Figure-6, clearly the result had been corrupted by noise. Hence, it is impossible to determine whether it has achieved steady state or not due to the presence of noise in the system. The only option is to calculate how close it is to the set point by using controller performance index which is the mean square error (MSE). The small value shows that it has good controller performance and closer to the set point. All measurement of MSE were taken from t=15001 second until t=25000 second with a duration of 10000 second. It was found out that it have value of 0.4031 for MSE criteria with oscillation maximum of 87.3065 and minimum of 83.0584 which resulted range of error between +2.3065 to -1.9416, which bring total error of 4.248.

The performance of the FOPIDer is shown in Figure-7. This experiment is executed to demonstrate the improvement in overall performance FOPID that was shown in Figure-6 by integrate error filter. Based on literature review, the original FOPID Controller that have been approximated using the Oustaloup's Recursive Approximation (ORA) method have a missing pole from origin as a consequences, it unable to reach steady state where in this case 85 degree Celsius. The parameter of error filter, *n* must be selected small enough, so it does not alter drastically system frequency. The improvement of implementation of error filter is seen in reducing number of maximum oscillation and settling oscillation that bring closer to the predetermine set point. However, it still suffer from having a big range of oscillation, same situation that wad observed in Fractional order controller. The real time result indicates that the FOPIDer have MSE of 0.3584 which much smaller than FOPID of 0.4031. Based on this result, it can be interpreted that the error that occur are subrationally reduced but the noise are still affecting the overall performances by having of 3.5734 that only reduction of 15.9% from original FOPID.

Figure-8 shows the effect of low pass filter when applied in the Fractional order Controller in SMISD plant. The result indicates that it unable to reach the predetermine set point of 85 degree Celsius. However, it reduced significantly the range of oscillation which is around 2.8561 degree Celsius where the minimum and maximum oscillation is around 84.3585 to 87.2149 degree Celsius with reduction of 32.8% as compared to original FOPID controller. During the approximation using ORA, it have been amplified sensitivity of derivative term. Slightly variation of noise causing the output to spikes hence causing the system to be oscillated as in Figure-6 and Figure-7. The FOPIDlp has number MSE of 0.4146.

After the results above is examined, it is ideal to have both features of FOPIDer controller and FOPIDlp controller. Both features of error filter and low pass filter into single FOPIDerlp controller. This new controller is able to eliminate the steady error and reduce effect of noise. Figure-9 shows that it able to reach the predetermine set point at 85 degree Celsius and have smaller range of oscillation where this indicate the effect of noise have substantially reduce. This controller have maximum and minimum oscillation of 85.9987and 84.0338 degree Celsius respectively that bring total error of 1.9649 which is about 53.7% improvement from original FOPID. In term of number of MSE, it recorded the lowest number of MSE, with 0.1163 which 71.14% improvement from original FOPID.

CONCLUSIONS

This study has been successfully implemented in the various FOPID Controllers and its variance in real time application. By integration of error filter in FOPID controller, the MSE is reduced substantially which indicates the overall error that occur to the system is reducing. Low pass filter is responsible in reducing range of oscillation in FOPID controller which originally its sensitivity of derivative term is amplified by ORA algorithm. By combining both features of error filter and low pass filter, the performance of the FOPID Controller in term of MSE is reduced significantly more that FOPIDer and range of oscillation decreased more than FOPIDlp.

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