Evaluation of Energy Consumption in Small Scale Distillation Pot based on Integral Control Signal for Real Time Implementation

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Abstract— **This paper presents the comparative performances of PID controller with several tuning rules that includes Ziegler-Nichols, Cohen-Coon and Integral Square Error (ISE)-Load that was based on real time implementation. The characteristic of water temperature of hydro distillation process have been modelled by obtaining First Order Plus Dead Time (FOPDT). In this study, a setpoint was set up to 80°C to evaluate those tuning rules in term of transient responses such as settling time, rise time and percentage of overshoot. Moreover, another performance criteria in term of energy consumption have been evaluated by using integral control signal. The result shows that PID controller with Cohen Coon tuning gives the best performances for transient analyses and also gives lower energy consumption compared to other tuning rules.**

***Index Terms*— FOPDT model, PID Controller, Step Test, Ziegler-nichols, Cohen-Coon, ISE-Load, Accumulated Control Signal**

I. Introduction

RECENTLY, there is a resurgence involving in the study of essential oil. Essential oil have great interest not only in research area but also have highly demand in the industry. It is because its offers diverse application such as in perfumery, food industry, aromatherapy, pharmaceuticals and cosmetics [1, 2]. Extraction process is a one way of having an essential oil where it separates the volatile component from the botanical plant. There are various method of extraction techniques such as steam distillation, hydro distillation, supercritical fluid extraction, microwave extraction and others [3]. Althogh hydro distillation is a conventional technique but it is still relevant and been used in industrial scale because it is simplest, selectivity, and inexpensive [4, 5].

There are several factors that contributing the quality and quantity in essential oil. These factors are temperature, pressure, distillation time, chemical composition and particle size [6]. However, temperature brings the most significant effect to the quality and the output yield [7-9]. Therefore, monitoring temperature control is the most important in extraction process and is chosen as a process variable to the proposed research. Conventional method like hydro distillation mostly are not control at all. Since the hydro distillation are not sensitive towards parameter changes, therefore controllers are embedded in order to overcome the problem and also to improve the performance of hydro distillation plant.

Process model is important before implementing the controller design as it is fundamental step for preparing an efficient process [10]. Furthermore, process models is essential which it can take various forms depend on their intended application as well as many controller design algorithm need such models. Commonly, first-order plus dead-time (FOPDT) is a simple process model that be used in many industrial processes [11-13]. This model has received interest among the researchers because it is easier and understandable to obtain the parameters such as gain, time constant and time delay [14, 15]. Moreover, FOPDT is a suitable model structure since it possess lower order compared to high order that makes the controller tuning method can be executed in an efficient manner [16]. Majority of tuning method for PID controller were derived from FOPDT model [15, 17].

Although there are vast developments of advanced control during recent years, PID controller is still preferable and popular as fact that more than 95% of the controller involves in process control industries [14]. Moreover, most of the industry today still use the conventional and trusted PID controller [16] than others. In the past few decades, there a variety of PID tuning method which are Cohen Coon (CC), Ziegler Nichols (ZN), ISE-Load [18] and others. The tuning parameter were involved such as gain, K_p, integral time, T_i and derivative time, T_d. The parameter tuning somehow can bring effects to the system performance if there is no proper method in tuning the parameters [19]. Therefore, tuning parameters is necessary in order to have better performance and accuracy in system response [20].

In process industries, distillation process consumes a lot of energy consumption [21]. The distillation process brings to high energy usage because the extraction process is very time consuming. It can be reported that in [22], the duration of the extraction took several days to complete in a single process and it leads to higher energy usage. Therefore, to solve this

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shortcoming, a controller have been developed to optimise the energy consumption which is based on an integral control signal approach.

This study had compared the real time for several tuning rules such as PID ZN, PID CC and ISE-Load techniques to regulate the water temperature using hydro distillation technique that based on performance comparison that includes settling time, percentage of overshoot and rise time. Besides that, another criteria on evaluation the performance in term of energy consumptionan has been evaluate by using an integral control signal that indicates the average amount of energy used. The remaining parts of this paper was organized as follows. Section II described the system description in term of experimental setup and data acquisition. The modelling using step test is explained in Section III. Section IV presents PID controller and the tuning rules. The next section introduced of an integral control signal. Section VI will be discussing the comparison result between simulation and real time and last section is the conclusion.

II. SYSTEM DESCRIPTION

A. *Small Scale Distillation Pot*

In this study, the experimental works are carried out on a Small Scale Distillation Pot (SSDP) which is located at Distributed Control System Laboratory of Electrical Engineering in UiTM, Shah Alam. Fig. 1 shows the plant set up of SSDP that comprises of steel distillation tank with 6-litre water that contained the raw material at the bottom, temperature sensor, copper condenser and heating element. Fig.2 depicts the hydro distillation process set up for this system. During operation, the water is heated by hot plate that will brought to boil and influence from hot water and steam will force the oil out from its glands. Then, the vapour mixture of water and oil will be condensed and produced a layer of oil and hydrosol at a collecting container..

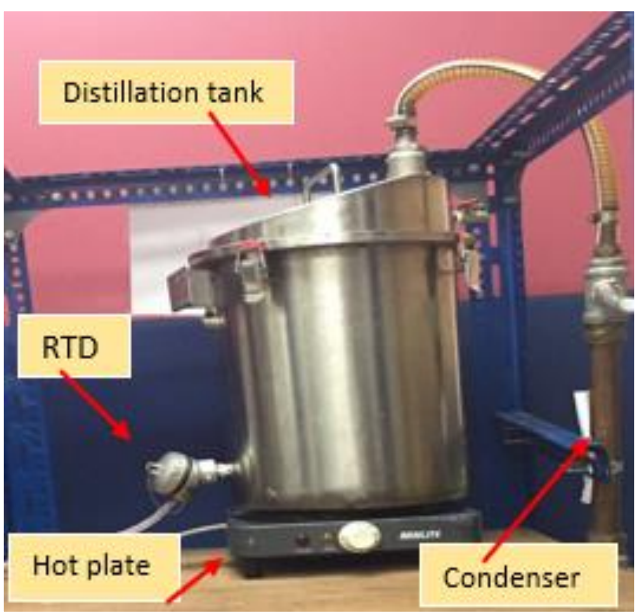

Fig. 1.Plant set up

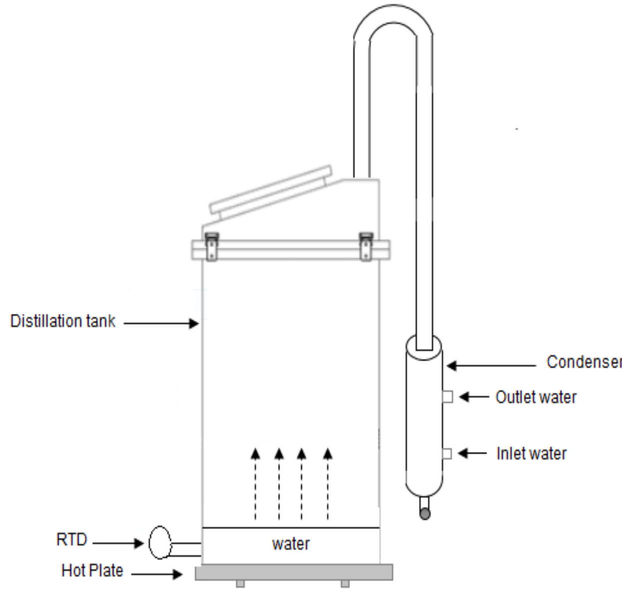

Fig. 2.Hydro distillation extraction process

B. *Hardware Commissioning*

This section explains the proposed water temperature control system integration for hydro distillation extraction essential oil process. Fig. 3 illustrates 3 main parts that are includes the process plant, computer control section and data acquisition via PCI-1716. The system consists of a hot plate as a heating element and microprocessor based power controller (STOM1) with 25A to drive the heater. The temperature of water will be measured by resistive temperature detector (RTD PT100) that is placed at the bottom of the plant. The conversion of the resistance to voltage was performed by signal converter (SENECA K109PT) with output ranging from 1V to 5V for temperature from 0°C to 120°C. The acquired data are obtained by using PCI-1716 Advantech data acquisition card to interface between computer and the hardware. The water temperature of the plant is controlled by STOM1 that produced the control signals from 0V to 5Vdc via digital-to-analog converter (DAC) that fed to the hot plate as an actuator to the plant. For software part, MATLAB Simulink is employed which the signal been generated. For this system, the sampling period is 1 second.

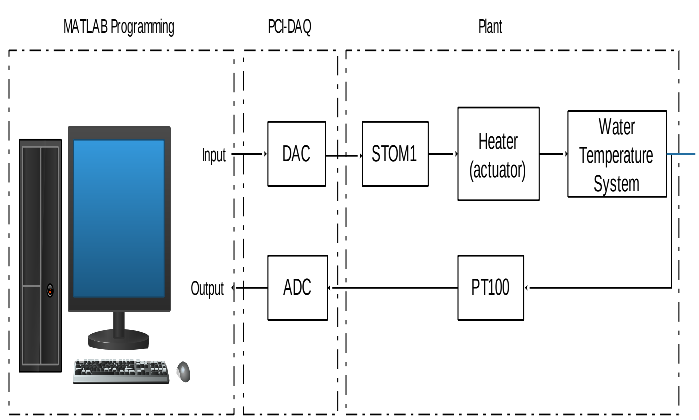

Fig. 3.Block diagram of the overall system integration

III. STEP TEST AND MODELLING

A. Step Test

Step test is one of the basic test used to establish the response characteristics of the system. The step test method is done by an open-loop experiment. This experiment is done by recorded the process until a steady state level archieved. From this step test, there are three parameters can be obtained which are time constant, τ time delay, θ and gain, Kp. Fig. 4 and Fig. 5 shows a 5V step that is an input signal to the system and water temperature response output during open-loop experiment respectively.

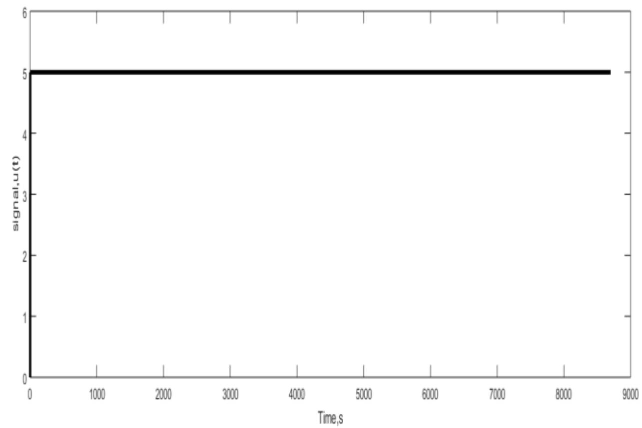

Fig. 4.5V step input signal

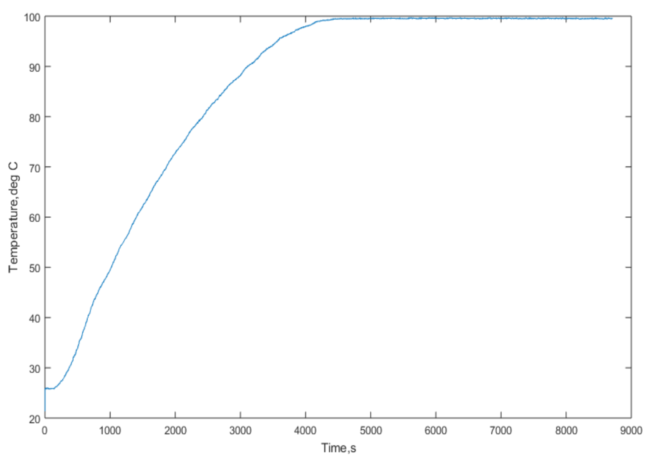

Fig. 5.Water temperature output response

B. FOPDT Model Structure

From the temperature output response by open loop test, a process reaction curve is used to obtain the FOPDT model. FOPDT model can be estimated based on two techniques which called as first method and second method. A first method known as graphical method is done by drawing the straight line at the steepest point of the response curve meanwhile the second method requires data at specific points which is much easier to be determined [23].

$$\frac{Y(s)}{X(s)} = \frac{K_p e^{-\theta s}}{\tau s + 1} \tag{1}$$

where

$Y(s)$ is the output of the process
$X(s)$ is the input
Kp is the process gain
τ is the time constant
θ is the time delay

In this study, the second method approach have been used as the following equation:

$$Temp\ 28.3\% = \left[\frac{28.3}{100}[Tmax - Tmin] + Tmin\right] \tag{2}$$

$$Temp\ 63.2\% = \left[\frac{63.2}{100}[Tmax - Tmin] + Tmin\right] \tag{3}$$

Fig. 6 illustrates the process of reaction curve in obtaining the FOPDT model by using second method. Therefore, the values that reaches 28.3% and 63.2% of its final value are used to obtain those parameters for FOPDT model that stated as follows:

$$Time\ constant, \tau = 1.5(t_{63\%} - t_{28\%}) \tag{4}$$

$$Time\ delay, \theta = t_{63\%} - \tau \tag{5}$$

$$Gain, K = \frac{Output, \Delta Y}{Input, \Delta U} \tag{6}$$

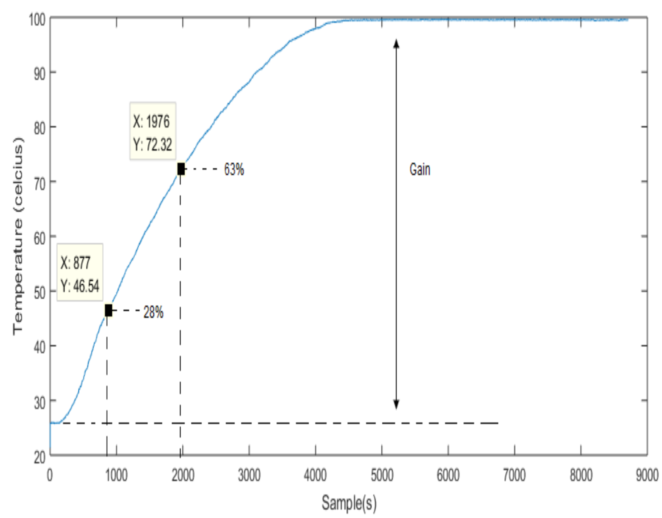

Fig. 6.Process reaction curve response

In this work, the sampling period is one second have been selected and the estimated model of FOPDT as in equation (7).

$$\frac{Y(s)}{X(s)} = \frac{14.71e^{-327s}}{1648.5s + 1} \tag{7}$$

IV. PID CONTROLLER

A. PID Description

PID is stands for Proportional term, Integral term and Derivative term. These terms interpreted in term of time which are *P* based on present error, I depends on accumulation of past error and *D* based on prediction of future error. This controller also have their own capability to control the parameter changes for the system which is unstable and undesired response such as large overshoot and longer settling time [24]. As PD can improve transient response while PI can improve steady state response the function of the combination of those terms can improve overall system response for both transient as well as steady state response [24, 25]. Moreover, this controller also able to minimize the time domain performance includes settling time, rise time and overshoot in the system [24]. The transfer function for the PID controller is given by equation (8)

$$G(s) = K_p + \frac{K_p}{T_i s} + K_p T_s\, s \qquad (8)$$

Where

K_p is the proportional gain
T_i is the integral time constant
T_d is the derivative time constant

As in equation (8), the parameter such as K_p, T_i, and T_d are known as the tuning parameters of PID controller. These parameters have to be tuned since each of the parameter gives affect that will reflect the performance and stability of the system.

Nevertheless, for real time application, existing PID controller is not appropriate to be implemented. It is because the system usually have higher frequency measurement noise. Therefore, to solve this shortcoming, minor modification have been done which is by using low pass filter that affect on the derivative term [26]. As the impact, this low pass filter can attenuate the noise that occur during the real time implementation. Thus, the modification of the derivative term can be obtained by equation (9).

Before modification, $K_p T_s\, s \;\rightarrow$

After modification, $\frac{T_d s}{(T_d/N)s+1}$ (9)

In (9), N is denoted as number of filter. The suggested value of N to be chose is in the range of 5 ≤ N ≤ 20 [26]. Therefore, the new transfer function for PID controller is stated in equation (10).

$$G(s) = K_p + \frac{K_p}{T_i s} + \frac{K_p T_d s}{(T_d/N)s + 1} \qquad (10)$$

B. PID Tuning Rules

PID controller is known as the controller parameters tuning process which in each mode (proportional, integral and derivative), there has a gain that are need to be tuned. However, the effectiveness of the controller is relies on the proper tuning of its parameter. Therefore, proper methodology of the controller parameters tuning is crucial in order to have quality of the control system unless the system may be unsatisfactory. Here, tuning of PID controller used those three terms that are important to achieve appropriate value of the desired response. This study have been focused on well-known tuning such as Ziegler Nichols, Cohen Coon and ISE-Load. Table 1 tabulated the formula for those tuning method used in this study.

TABLE I
ZN, CC AND ISE LOAD FORMULA FOR PID CONTROLLER TUNING RULES

PID Tuning Rules	***Proportional Gain, K_p***	***Integral Time constant, Ti***	***Derivative Time Constant, Td***
ZN	$\left(\frac{1.2}{K}\right)\left(\frac{\tau}{\theta}\right)$	2.0θ	0.5θ
CC	$\frac{\tau}{K\theta}\left(\frac{4}{3}+\frac{\theta}{4\tau}\right)$	$\theta\left(\frac{32+6\theta/\tau}{13+8\theta/\tau}\right)$	$\theta\left(\frac{4}{11+2\theta/\tau}\right)$
ISE-Load	$\frac{1.473}{K}\left(\frac{\theta}{\tau}\right)^{-0.970}$	$\frac{\tau}{1.115}\left(\frac{\theta}{\tau}\right)^{0.753}$	$0.550\tau\left(\frac{\theta}{\tau}\right)^{0.948}$

The process gain, *K*, time constant, *τ,* and time delay, *Θ* that used for calculating the tuning parameters of PID controller were obtained from open loop step response by using second method that explained in Section III. Table 2 shows the calculated parameters of the PID controller.

TABLE 2
CALCULATED PID CONTROLLER PARAMETER

PID Tuning	***Proportional Gain, K_p***	***Integral Time constant, Ti (seconds)***	***Derivative Time Constant, Td (seconds)***
ZN	0.4106	655	163.75
CC	0.473	745.09	114.939
ISE-Load	0.4802	437.825	195.917

V. INTEGRAL CONTROL SIGNAL

Evaluation of the control performance of the system are includes Integral Square Error (ISE), Integral Absolute Error (IAE) and Intgeral Time-weighted Absolut Error (ITAE). All this performance tests are evaluated that based on the error. Unlike Integral Control Signal (ICS), the performance is evaluated based on the control signal that is output from the controller as shown in Fig. 7. Basically, the principle of ICS is the accumulated of control signal over the time. It indicates that, how much amount of the energy consumption have been utilized for the system. In evaluating the ICS approach, Eqn (9) has been considered in determining the energy consumption. In this study, this method has been used to evaluate the energy usage for each of PID tuning rules.

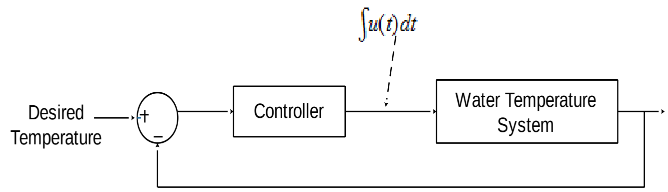

Fig. 7:Part of integral control signal measurement

$$ICS = \int_0^\infty u(t)\,dt \tag{9}$$

VI. Result and Discussion

This section contains the result of real-time experimental result for several tuning rules. The result will based on the performances of the controllers in real time implementation. Moreover, another criteria have been evaluataed in term of energy consumption by using integral control signal. The several of PID controller tuning includes ZN; denotes as PID-ZN, CC;denotes as PID-CC and ISE-Load denotes as ISE-Load.

A. Result in Term of Transient Response Analysis

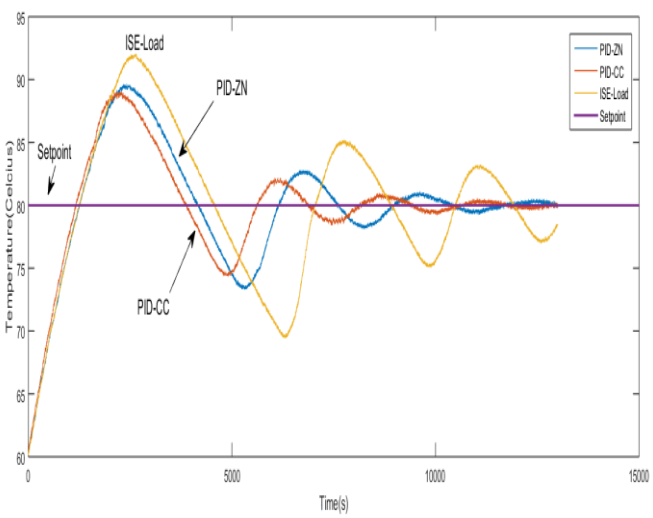

Fig. 8:Result of transiet response of real-time implementation

TABLE 3
Transient Response Analyses

	Rise Time, T_r (s)	Settling Time, T_s (s)	Overshoot (%)
PID CC	925.094	12365	11.320
PID ZN	979.833	12911	12.151
ISE-Load	1002.1	12932	17.466

*shaded box represent the best response of the transiet response

Fig. 8 the results of transient response by real-time implementation. Table 3 tabulated the performances of the controller for real time implementation that includes rise time, T_r, settling time, T_s and percentage overshoot. The desired temperature was set at 80°C which intended to study and compare the stability and capability of those three tuning rules for hydro distillation process for real-time implementation.

Based on the real-time result shown in Fig. 8, it clearly shows that PID CC gives the best response among those tuning rules for real time application. For example, PID CC experienced faster in rise time that difference about 54.739s and 76.906s compared to PID ZN and ISE-Load respectively. Moreover, for settling time, ISE-Load takes longer time with the differ is about 567s for ISE-Load and 546s for PID ZN. All the tuning rules have experienced the overshoot phenomena at 2245s for PID CC, 2398s for PID ZN and 2609s for ISE-Load. On percentage of overshoot result, it shows that PID CC produces the smallest percentage of overshoot and ISE-Load experienced the larger overshoot. For real-time experimental result analysis, it can be conclude that PID CC gives better result than others because PID CC can fulfill all the requirement of transient response performance. Referring to Fig. 8, for both PID CC and PID ZN, the response starts to reach steady state but difference with ISE-Load, the response did not show any tendency to reach the steady state of the system.

B. Result in Term of Energy Consumption

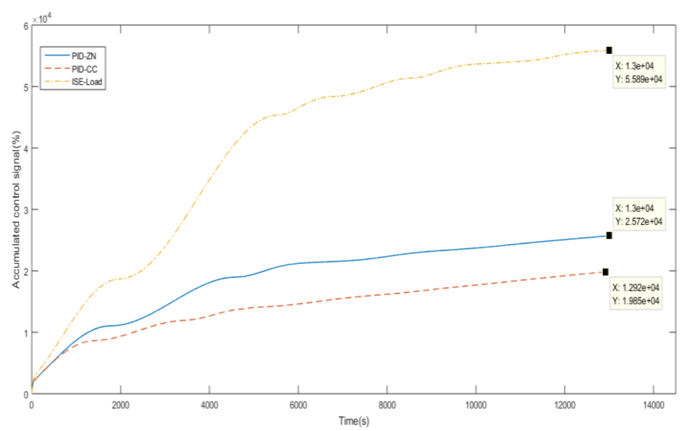

Fig. 9:Accumulated control signal for real-time implementation

TABLE 4
Accumulted and Averaged Control Signal Based on PID CC, PID ZN and ISE-Load for Real Time Implementation

	PID Tuning		
	PID CC	PID ZN	ISE-Load
Accumulated Control Signal	1.985×10^4	2.572×10^4	5.589×10^4
Average Control Signal	1.527%/s	1.978%/s	4.299%/s

*shaded box represents the lowest value in term of energy consumption

One method in evaluating the performance of the controller can be evaluated by transient response analyses whereas, in this study, this criteria have been focused that includes rise time, settling time and percentage of overshoot. On the other hand, in this study also, the control signal has been accumulated to evaluate the energy consumption for hydro distillation process by using ICS approached. ICS method has been applied as an additional criteria that need to segregate the controller performances in term of energy consumption.

The accumulated control signal that obtained by real-time implementation has been demonstrated in Fig. 9. From the result obtained, the accumulated control signal for ISE-Load shows higher responses than others. Table 4 tabulated the comparative result of tuning rules that shows PID CC gives the smallest percentage over time compared to others. The differ percentage over time is about 0.451 for PID ZN and 2.772 for ISE-Load. It is indicate that the PID CC consumes less energy usage. Meanwhile, ISE-Load produced higher percentage over time means that this tuning rules consumes more energy consumption than others. Based on the result, it clearly shows that, PID CC brings to less energy comsumption compared to PID ZN and ISE-Load.

VII. Conclusion

This paper evaluated the PID controller performance based on several tuning rules from FOPDT model. For the real-time implementation, it can be concluded that PID CC gives the best performances among the others whether in term of transient response performances and also in term of energy efficiency compared to PID ZN and ISE-Load.

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