FOPDT Modelling and Controller Comparative Study for Smart Tube Aqua Filter (STAF)

Ahmad Aftas Azman, Nurul Nadia Mohammad, Norbaya Hj Sidek, Mohd Fozi Ali,
Ilyani Akmal Abu Bakar, Mohd Nasir Taib, Mohd Hezri Fazalul Rahiman

***Abstract*-Malaysian Meteorological Department statistics stated that rainfall in this country is among the highest the world with 2500mm a year. Therefore, the phenomenon of flooding often occurs in Malaysia. Flooding will cause water to become cloudy or turbid. This situation is getting worse as demand for fresh water is higher than supply. Therefore, researchers have designed several of water filter system to overcome these issues. Not to mention, the usage of the chemical as a purifying agent such as coagulant and flocculation process for turbidity water purification. In this study, we used Aluminium Sulphate $Al_2 (SO_4)_3$ as a coagulant agent, and Smart Tube Aqua Filter (STAF) plan in flocculation process. This plant is modeled by first order plus time delay (FOPDT) model, to explain the behavior of processes. Model Predictive Controller (MPC) and proportional integral derivative (PID) controller are applied to control the process. Robustness and efficiencies of the controller are analyzed and evaluated, and then a comparative study is conducted for the best performance of transient response. Finally, we found that MPC gives the best performance of transient response in robustness test (step test has faster settling time, of 5035.0 sec and overshoot percentage of 0.0917%, Setpoint change test has performed better in five (5) categories of the test), compared to PID controllers for STAF simulation test.**

***Index Terms* - Aluminium Sulphate $Al_2(SO_4)_3$, FOPDT, MPC, PID, and Turbidity.**

I. INTRODUCTION

ACCORDING to the rainfall statistics carried by Malaysian Meteorological Department, rainfall in Malaysia is 2500mm a year; which has been among the highest rainfall capacity in the world [1]. Due to this factor, the possibility of flooding is high. Therefore, floods cause several problems such as water-borne diseases, clean water source, and floods. This scenario is getting worse as the demand for fresh water is higher than supply [2]. More importantly, floods cause the source of clean water to become turbid. Under those circumstances, the researchers using the various method of water filtration system techniques including sand, carbon, chemical, and others in the filtration process. Turbidity is measured by Nephelometric Turbidity Units (NTU) which can be measured by determining the amount of light scattering in water, and the amount of dispersion of this light is influenced by particles (clay, silt, and sand), plankton, microbes, algae and other substances [3]. In this study, we use a chemical method through a process called coagulant and flocculent [4], to clarify murky water. The aluminum sulphate $Al_2 (SO_4)_3$ acts as a coagulant and Smart Tube Aqua Filter (STAF) plan is designed for flocculation process. The advantages of STAF are easy to install, portable and lightweight. Furthermore, the STAF lifespan is longer, unlike other water filters. If the raw water turbidity rate is too high, the lifetime of filter decreases due to frequent backwashing activities. In addition, STAF has no water filter element for backwashing. As aforementioned, STAF uses aluminum sulphate $Al_2 (SO_4)_3$ as coagulant agent and an appropriate dosage of aluminum sulfate $Al_2 (SO_4)_3$ is important to control the water purification. Above all, consumers health should also be taken into consideration, indeed an overdose of aluminum sulfate $Al_2(SO_4)_3$ will affect human health [5].

There is a standard outlined for determining water quality parameters (WQP) for each water resource referred by World Health Organization (WHO) [2]. The best turbidity level of drinking water endorsed by WHO is below than or equal to 1 NTU. For Malaysia, the Ministry of Health has stated that the allowable turbidity level is below than 5 NTU [6]. Coagulation is a part of the important process in water treatment wherein the proper coagulant dosage ensure the harmless raw water supply and free impurities [7][8]. In addition, coagulation is a complicated physical-chemical process that is influenced by raw water turbidity, temperature, flow, and pH value. In light of this, the process shows a high nonlinearity characteristic, large time delay, time-variant and uncertainty [9]. In this study, we are focused on water turbidity purification.

Many previous studies on PID tuning devoted to creating a better performance and various PID controller tuning methods had been proposed especially for first order plus time delay (FOPDT). Ziegler-Nicholas tuning [10] and Cohen-Coon tuning [11] are the pioneers in classical

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Ahmad Aftas Azman is with the Politeknik Sultan Salahuddin Abdul Aziz Shah and PhD candidate at Faculty of Electrical Engineering, Universiti Teknologi MARA, 40450 Malaysia (e-mail: naftasya@gmail.com).

Nurul Nadia Mohammad, Mohd Nasir Taib, & Mohd Hezri Fazalul Rahiman is with the Faculty of Electrical Engineering, Universiti Teknologi MARA, 40450 Malaysia

Norbaya Hj Sidek, Mohd Fozi Ali, & Ilyani Akmal Abu Bakar, is with the Faculty of Civil Engineering, Universiti Teknologi MARA, 40450 Malaysia.

(corresponding author & email: Mohd Hezri Fazalul Rahiman & hezrif@ieee.org).

techniques that are widely used in many industrial applications. Model predictive control (MPC) is considered as an advanced control scheme to optimize wastewater treatment plants (WWTPs) [10][11]. It is proven that with the application of MPC, 25% of aeration cost can be saved in an activated sludge plant [10]. The real monitoring and appropriate models of process behaviors are required for MPC become successful, especially on chemical coagulant online measurement [12].

Furthermore, in this study, MPC and PID controllers with Ziegler Nichols (ZN) and Cohen-Coon (CC) tuning methods are applied to STAF plant. Consequently, the results are analyzed and evaluated based on transient response analysis performances of controller's robustness tests using Matlab simulation.

This paper is outlined with simple explanations of flood, turbidity, and controller in Section 1. Section 2 elaborates the plant description in detail followed by the plant operation in Section 3. Section 4 focuses on the explanation of open loop controller followed by a brief implementation of PID controller in Section 5 and a detail of model predictive controller in Section 6. Subsequently, Section 7 represents the results and discussions of the study. The paper is concluded in Section 8.

II. PLANT DESCRIPTION

Smart Tube Aqua Filter (STAF) consists of input and output components, in which the turbidity sensor module acts as an input and proportional solenoid valve and water pump as the output. These components are connected to Arduino mega board controlled by the computer as shown in Fig. 1. MATLAB software is to monitor and analyzed the input and output components. The data acquisition modules are required where Arduino mega card is used as the data acquisition module. Nephelometric Turbidity Unit (NTU) level of water is measured by turbidity sensor at the output stage. To control the amount of aluminium sulphate $Al_2(SO_4)_3$ in coagulation process, a proportional solenoid valve is used to control the liquid form of aluminium sulphate, that is mixed with artificial clay water. In flocculation process, the water pump is used to regulate the retention time.

Fig. 2 shows the pilot plant for Smart Tube Aqua Filter (STAF), located at 'Fakulti Kejuruteraan Elektrik' (FKE) Universiti Teknologi Mara. In addition, STAF is designed in two (2) modes of controls, which allows the system to control in manual or automatic modes.

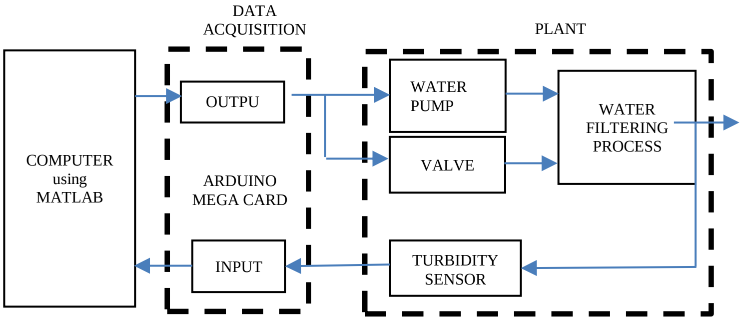

Fig. 1: Block Diagram Smart Tube Aqua Filter (STAF)

Fig. 2: Smart Tube Aqua Filter (STAF) Pilot Plant

III. PLANT OPERATION

Flood water is very prone to contamination and needs to be treated. This could be resolved with chemical dosage, namely coagulation process in water filter treatment. For instance, an inorganic coagulant (e.g., aluminum and ferric salts) is used to remove debris and suspended solid in turbidity water. In this study, we used aluminium sulphate $Al_2(SO_4)_3$ as coagulation agent. In addition, the use of aluminum sulphate $Al_2(SO_4)_3$ will reduce the turbidity level effectively [13]. Fig. 3 shows the operating flow of STAF water purification of the study. The raw water is channeled to the mixing tank and the aluminium sulphate $Al_2(SO_4)_3$ is added accordingly. This process is called coagulation. Then, the water is pumped to the mixing tank for flocculation process with aluminum staging filtration. In aluminum staging filtration, the Polyvinyl chloride (PVC) pipe with 50mm diameter x 4 feet tall in dimension is used. The aluminum staging filtration pipes are stacked vertically and connected by five (5) cylinder tubes. The function of these cylinders is to trap the suspended solid particles at the bottom of the tubes, separate the suspended particles and dissolved from the murky water by flocculation processes. Once completed the five staging tubes, the water is purified as clean water. Finally, the turbidity sensor measures the level of water clarity in the unit of NTU.

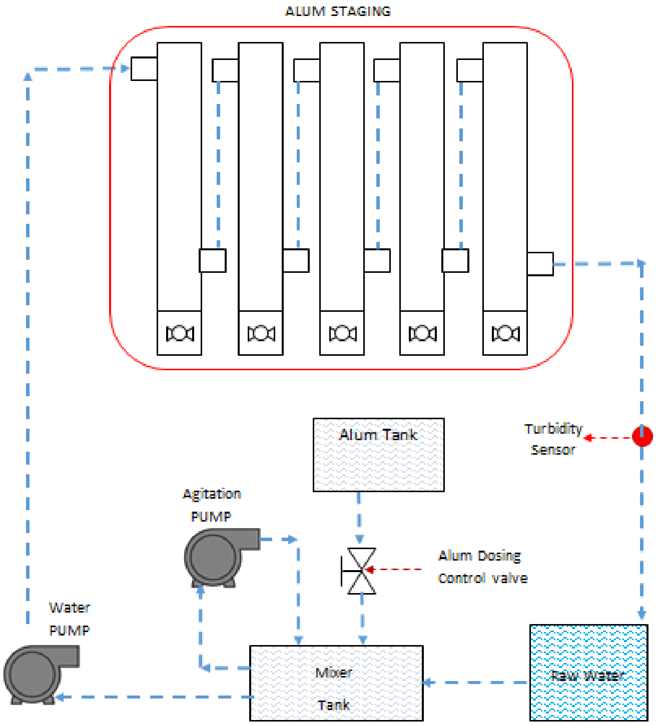

Fig. 3: Smart Tube Aqua Filter (STAF) Schematic Diagram

IV. OPEN LOOP CONTROL

Particularly, the open loop controller does not affect the input signal related to control action. Therefore, the open-loop system is not defined by the output signal or condition that is measured nor “fed back” for comparison with the system setpoint or input signal. Even though there is a load disturbance on the system, it is beyond the control for open-loop controller in determining how the process reacts to a disturbance, so the controller’s tuning is irrelevant when feedback is disabled [14][15]. The open loop control for Smart Tube Aqua Filter (STAF) as shown in Fig. 4 produces the reaction output curves and subsequently represents the modeling process as shown in Fig. 8. The reaction output curves are probably the most popular output representation in identifying the dynamic model. Consequently, it is simple to perform and provide adequate models for many applications. Indeed, first order plus dead time (FOPDT) is restricted to this model, where *X(s)* and *Y(s)* is the input and output, respectively. The expression of modeling transfer function is governed by in Equation 1 [16],

$$\frac{Y(s)}{X(s)} = \frac{Kpe^{-\theta s}}{\tau s+1}. \qquad (1)$$

Where the time constant *(τ)*, dead time *(θ)* and proportional gain *(Kp)* are obtained from the reaction output curves.

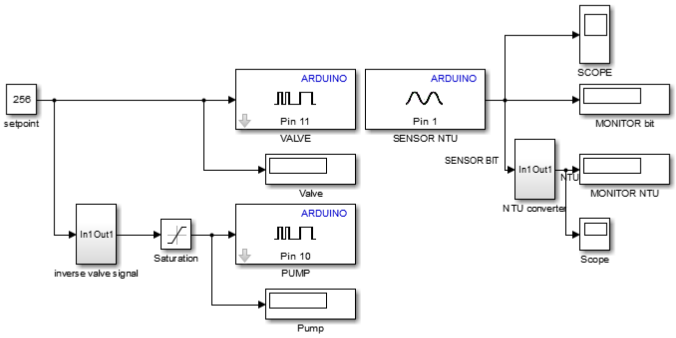

Fig. 4: STAF Simulink Open loop Control

V. PID CONTROLLER

Controller is the brain of a system; there are various types of a control system such as P, PI, and PID to the advanced control techniques. Above all of the controllers, there is about 95% of process control used PID controller. PID is easy to implement, low maintenance and robust. Furthermore, PID is also easy to understand and has a simple structure system [17]. PID controller is widely used in industries for various types of processes and many tuning models are proposed over five decades. Tuning of the PID controller uses the right techniques such as Ziegler Nichols (ZN) and Cohen-Coon (CC) tuning methods (see Table 1) [18][19]. There are many tuning methods that can be implemented for PID controller. In this study, a parameter of proportional gain *K* and time constant T_i and T_d are tuned and the process control performance is monitored [20].

PID controller continuously calculates the error value *e(t)* as the difference between the desired set point and measured process variable. The PID controller applies the proportional, integral, and derivative terms [21]. The controller attempts to minimize the error over a time by adjustment of a control variable *u(t)* as given by Equation (2).

$$u(t) = Kp\, e(t) + Ki \int_0^t e(\tau)d\tau + Kd\, \frac{de(t)}{dt} \qquad (2)$$

where:-

Kp	*proportional gain,*
Ti,	*integral time constant, and*
Td	*derivative time constant*

The PID error can be controlled by the position of the control valve, the speed of the motor pump or liquid flow. The Simulink PID block controller utilizes in this study is shown in Fig. 5.

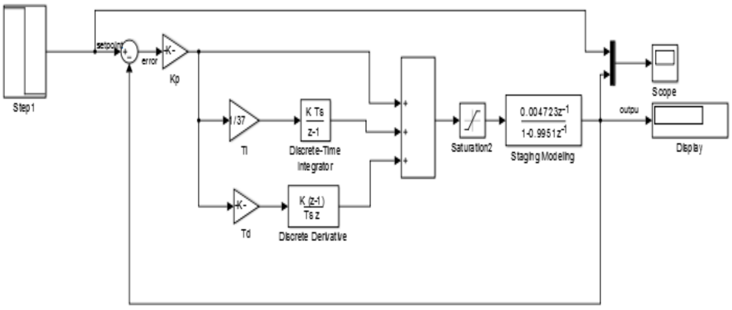

Fig. 5: STAF Simulink PID Control

VI. MODEL PREDICTIVE CONTROL

Model Predictive Control (MPC) was introduced in the 1970s and is still relevant for both industry and academia sectors until today. Besides, MPC control strategy is widely used in process control industry, and in the dynamical system since this controller can predict the future response of plant [22]. MPC can anticipate the dynamic system response over a specific time, based on a system model and compute optimal control action by minimizing a cost function as in Fig. 6 [23][24]. By referring to Fig. 7, the steps involve the factor such as cost function, future state/output prediction and control signal for MPC control procedure.

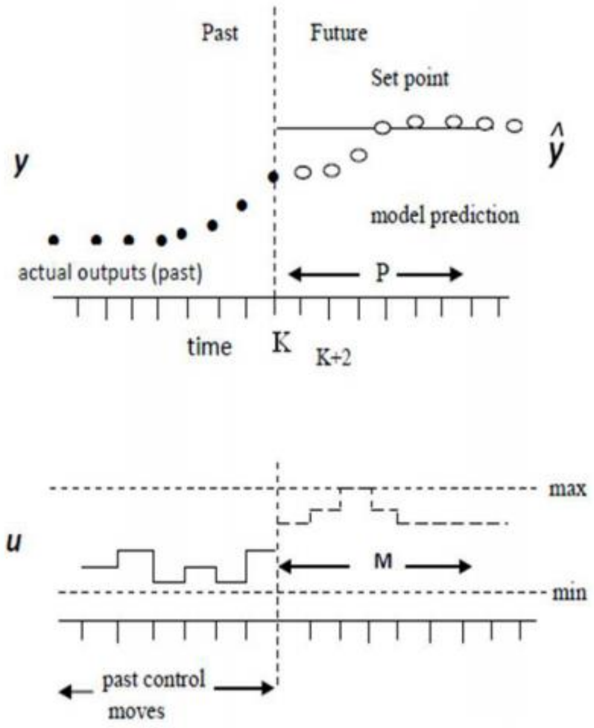

Fig. 6. Basic concept of model predictive control [24]

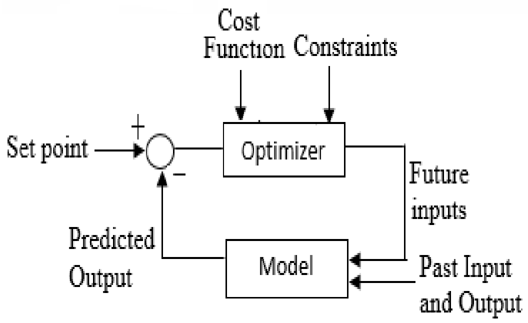

Fig. 7: Block diagram of MPC

The state space nominal model of single input single output (SISO) for STAF plant is shown in Equations (3) and (4):

$$x\,(k+1) = Ax(k) + B\Delta u(k) \tag{3}$$

$$y(k) = Cx(k) \tag{4}$$

where
A, B and C are the matrices,
x, state variable,
u, control input and
y, output performance.

The data set point vector is approximated as in Equation (5):

$$R_S^T = [1\;1\ldots\;1]1 \times N_P\; \times r(ki). \tag{5}$$

The cost function of the MPC structure can be expressed as (6):

$$J = (R_S - Y)^T(R_S - Y) +\; \Delta U^T \tag{6}$$

The predicted output variable Y can be found by Equation (7):

$$Y = [y(ki+1|ki)\; y(ki+2|ki)\;\ldots y(ki+N_P|ki]^T \tag{7}$$

Then, the optimal control signal, ΔU can be obtained by solving the optimal sequence as shown in Equation (8):

$$\Delta U = [u(ki) - u(ki-1)\; u(ki+1) - u(ki) \ldots\; u(ki+N_C-1) - u(ki+N_C-2)]^T \tag{8}$$

where:

$y(ki+J\|ki)$	predicted output of model at time $ki+J$ gave the output at the time ki
$r(ki)$	reference signal at the time ki
$u(ki+J)$	control parameter
$\bar{R}$	tuning parameter.
N_P	prediction horizon and
N_C	control horizon.

A. *Tuning Rule*

There are two (2) categories classified under the controller tuning methods namely:-

i. Open-loop method and
ii. Closed loop method

The open loop method is suitable in an uncontrolled condition wherein the plant operates in manual state whilst the closed loop tuning method is an automated tuning system in plant operation [25]. Furthermore, the most popular techniques for tuning rules are Cohen-Coon (CC) and Ziegler Nichols (ZN) tuning method. Ziegler Nichols (ZN) tuning rule was introduced in the mid-20th century and is the beginning of systematic tuning rules for PID control. Another method of tuning PID controller is Cohen-Coon (CC) that has been introduced in 1950 [22]. The PID tuning rules for ZN and CC are elaborated in Table I.

TABLE I
PID TUNING RULE

PID Tuning	Proportional Gain *Kp*	Integral Time Constant, *Ti*	Derivative Time Constant *Td*
ZN	$\frac{1.2\tau}{K\theta}$	2θ	0.5θ
STAF PIDZN	*10.913*	1137	284.25
CC	$\frac{1.35}{K}\ x\ [\frac{\tau}{\theta} + 0.185]$	2.5θ x $\frac{\tau+0.185\theta}{\tau+0.611\theta}$	0.37θ x $\frac{\tau}{\tau+0.185\theta}$
STAF PIDCC	*13.394*	1314.84	202.9408

B. *Simulation test*

In this study, we apply three types of testing techniques for capturing the performances of transient response, namely step test, set point change and load disturbance test. Moreover, these tests have been implemented to evaluate the robustness of controller performance.

First of all, the step test is performed by supplying certain values of a unit step function as input into a system [26]. In this study, a value of 1003 byte is set as an input value for STAF pilot plant as shown in Fig. 9. In fact, the value of 1003 byte is equivalent to 50 NTU of turbidity water level. Furthermore, setpoint change is a multiple-staged of set input value that is applied as an input to the process. In this study three (3) inputs of setpoint values for the process have been set.

The setpoint values are ‘1003, 1013 and 1021’ bytes, that are equivalent to 50, 25 and 5 NTU of turbidity water level respectively. As depicted in Fig. 10, three (3) setpoint values for STAF can be referred. A setpoint change input passed through both the controller and the process, even without any feedback. As a result, the mathematical inertia of the controller combines with the physical inertia of the process to make the process’s response to a set point that has been manipulated [27]. The load disturbance test is a set of test, where a process is interrupted with a certain load at a specified time. The purpose of this test is to monitor how fast the recovery time of the process is taken. In this study, the process is interrupted at 20000 sec of process time as shown in Fig. 10; i.e. this test is performed by monitoring a timing recovery by disturbance to a process plan.

VII. RESULTS AND DISCUSSIONS

Particularly in this study, we set a 1023 byte as a setpoint value; indeed this is equivalent to 5V that gives full power for the water pump and proportional solenoid valve in open loop test. The turbidity sensor collects the data and sends them as an output result for a reaction curve.

A. *Reaction Curves*

Three (3) main dynamic of system components such as dead time (θ), gain (k) and time constant (τ) can be identified by using process reaction curve. There are two common techniques used in the process reaction curve. The first method is adapted from Ziegler-Nichols (1942) in [28], that determines the process characteristics based on the maximum slope of the output response versus time plot. The second method is based on the graphical calculation as shown in Fig. 8. Marlin suggested that the second method is much more preferred due to difficulty in evaluating the maximum slope and typically larger errors which occur in estimating the parameters such as k, τ and θ [29]. The second method delivers a much better performance than the first method, where the second method involves two points of intersection (t28 and t63) in process reaction curve, unlike a single of point intersection in the first method.

As a result, the reaction curves have been generated from the open loop controller output as shown in Fig. 8. Using the graphical calculation extracted from STAF reaction curves; the parameters of Δy, 0.63Δ, t63%, 0.28Δ, t28% have been determined as follows;

Δy = 1023 – 880 = 143 byte

0.63Δ =90.09 + 880 = 970.09 byte
∴ t63% = 2319 sec

0.28Δ = 40.04 + 880 = 920.04 byte
∴ t28% = 394 sec

The time constant (τ), dead time (θ); and proportional gain *Kp* are calculated as shown in Equations (9),(10) and (11) respectively:

Time constant (τ);

$$\begin{aligned} \tau &= 1.5(\mathrm{t63} - \mathrm{t28}) \\ &= 1.5(2319 - 394) \\ &= 2887.5 \text{ sec} \end{aligned} \tag{9}$$

Dead time (θ);

$$\begin{aligned} \theta &= \mathrm{t63\%} - \tau \\ &= 2319 - 2887.5 \\ &= 568.5\text{sec} \end{aligned} \tag{10}$$

Gain (Kp);

$$Kp = \triangle y/\triangle u \tag{11}$$

= (143) / (256)
=0.5585.

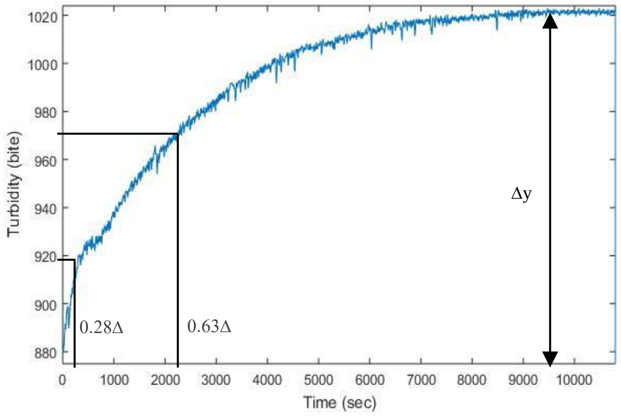

Fig. 8: STAF Reaction Curves

B. *First Order Plus Dead Time (FOPDT) Modelling*

A common empirical description of many stable dynamic processes is a first-order linear system with time delay. The FOPDT model is used to obtain initial controller tuning constants. The effect of the three adjustable parameters of FOPDT is shown in Equation (12).

$$Gp(S) = \frac{Y(S)}{U(S)} = \frac{Kp\, e^{-\theta ps}}{\tau ps+1} \qquad (12)$$

Where the following parameters are obtained from the reaction curves shown in Fig. 8;

$Kp = 0.5585$, $\theta = 568.5$, $\tau = 2887.5$

$$Gp(s) = \frac{Y(s)}{U(s)} = \frac{0.5585\, e^{-568.5s}}{2887.5s+1}.$$

This model is used in Matlab simulation for various types of controllers which represent the process plant. Furthermore, from the modeling process of STAF pilot plan, the continuous PID and MPC simulations are proposed as shown in Fig. 5 and 7, respectively. The performance of MPC, PID ZN, and PID CC are monitored and evaluated.

C. *Step Test*

Fig. 9 shows the simulation result of 1003-byte step test. In Table II, we found that the faster rise time controllers are PID ZN and PID CC with values of 1237.8 sec, while MPC is 4036.0 sec. Meanwhile, for settling time, MPC has a faster time of 5035.0 sec compare to PID ZN (5871 sec) and PID CC (6457.9 sec). Subsequently, for overshoot percentage, we found that MPC has better performance with 0.0917% as compared to PID CC (7.34%) and PID ZN (7.5%). Therefore, it is proven that the MPC has a better performance than PID ZN and PID CC for step test simulation.

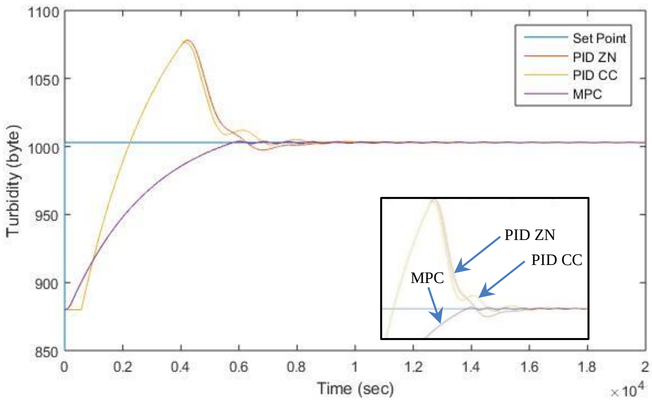

Fig. 9: Simulation Step test output

TABLE II
PID STEP TEST

Controller/Tuning	Rise Time (sec)	Settling Time (sec)	% Overshoot
PID – ZN	**1327.8***	5871.0	7.5000
PID – CC	**1327.8***	6457.9	7.3402
MPC	4036.0	**5035.0***	**0.0917***

‘*’ shows better performance.

PID ZN	1*
PID CC	1*
MPC	**2***

D. *Set Point Change*

Table III delineates the performance of each controller based on rise time, settling time and overshoot percentage with ‘1003-, 1013- and 1021-’ byte set points. The controller performance for each stage of the setpoint is marked as ‘*’ to indicate as the best performance at each segment. From the simulation result, we found that MPC had 5* and performed better than PID ZN (2*) and PID CC (2*) as shown in Table 3. It is concluded that MPC has a better performance than to PID ZN and PID CC for setpoint change simulation test.

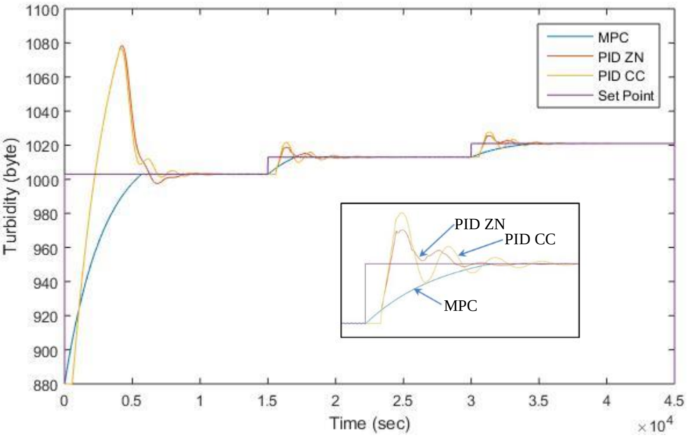

Fig. 10: Simulation set point change output

TABLE III
PID SETPOINT CHANGE

Controller/ Tuning	Rise Time (sec)	Settling Time (sec)	% Overshoot
	Set Point 1003		
PID ZN	**1327.8***	5878.3	7.5225
PID CC	1328.4	6462.3	7.3578
MPC	4024.6	**4891.2***	**0.0334***
	Set Point 1013		
PID ZN	309.6664	3239.8	0.5689
PID CC	**272.7916***	5891.9	0.8546
MPC	1581.0	**1865.2***	**0.0163***
	Set Point 1021		
PID ZN	300.3905	**3224.2***	0.4455
PID CC	**267.3632***	5881.4	0.6725
MPC	3464.3	4159.4	**0.0019***

‘*’ shows better performance.

PID ZN	2*
PID CC	2*
MPC	**5***

E. Load Disturbance Test

The load disturbance has been set at 20000 sec and 21 bytes as a disturbance load for the process. The simulation output result for load disturbance test is shown in Fig. 11. By comparing the controller output of PID ZN, PID CC and MPC for this test, it shows that the recovery time of PID ZN is much faster than that of MPC and PID CC. Therefore PID ZN has better performance than MPC and PID CC as shown in Table IV.

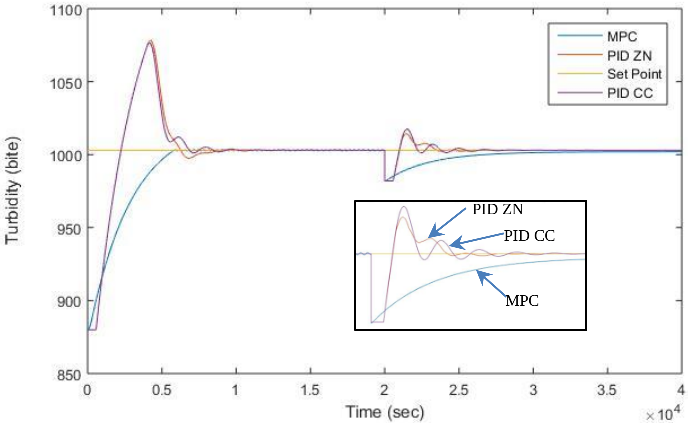

Fig. 11: Simulation load disturbance output

TABLE IV
PID LOAD DISTURBANCE TEST

Controller/Tuning	Recovery Time (sec)
PID ZN	**5490***
PID CC	7890
MPC	6760

‘*’ shows better performance

Consequently, among the three (3) types of controllers (MPC, PID ZN, and PID CC), we found that MPC has much better performance in terms of settling time and overshoot than that of PID ZN and PID CC at step test and setpoint change test. However, PID ZN has a faster recovery time at load disturbance test. Therefore, MPC controller provides a better performance on overall robustness test [30].

VIII. CONCLUSION

The Smart Tube Aqua Filter (STAF) is successfully modeled using FOPDT model. This model is expanded in designing the controller that representing a simulation of STAF. This study has evaluated the performances among the controllers of PID ZN, PID CC and MPC for robustness test. The performance is based on transient responses analysis for STAF. From the comparative analysis (step, set point change and load disturbance test), we conclude that both PID controllers have poor performances due to the large percentage of overshoot and low accuracy in term of steady-state response as compared to MPC.

Step test result show, MPC has a faster settling time, of 5035.0 sec compare to PID ZN (5871 sec) and PID CC (6457.9 sec). Subsequently for overshoot percentage, found that MPC has better performance with 0.0917% as compared to PID CC (7.34%) and PID ZN (7.5%). While for overshoot percentage, found that MPC has better performance with 0.0917% as compared to PID CC (7.34%) and PID ZN (7.5%). While, for setpoint change test, controller performance for each stage of the setpoint is marked as '*' to indicate as the best performance at each segment and found that MPC had 5* and performed better than PID ZN (2*) and PID CC (2*). However, PID ZN has a faster recovery time (5490 sec) at load disturbance test compare to PID CC (7890 sec) and MPC (6760 sec). Under those circumstances, it is concluded that MPC gives the best performance of transient response in robustness test, as compared to both PID ZN and PID CC controllers for STAF simulation test.

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