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Model Reference Adaptive Control for Deaerator Pressure and Level System

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Abstract: Deaerator is one of the most important plants in industry, especially chemical industry. The goal of the deaerator is to release oxygen from the water so that the pipes and boilers are not corrosive. Controls of pressure and level in deaerator are needed to be done so the process goes well. Most industries use a PI control system to control the pressure and level of the deaerator. The PI control system has a weakness when there is a disturbance, the system must tune back one by one of each instrument that caused losses in terms of economic and material. Therefore, it needs a control method that can adapt to the disturbance. Model Reference Adaptive Control (MRAC) is one type of control methods that can harmonize to the changes of plant parameters so that the output system could be achieved in accordance with the reference model. Furthermore, the MIT Rule is used to update controller parameter of Model Reference Adaptive Control method. The results show the MRAC is able to yields the greater response compared to PI controllers.

Keywords:deaerator, level and pressure control, Model Reference Adaptive Control, MIT Rule.

1. Introduction

Most industries need steam to run their production process. There is one problem that occurs in the boiler, which is oxygen-induced corrosion. Deaerator is an important equipment to remove the oxygen and carbon monoxide in condensation water and to heat the condensation water to saturation temperature [1]. There is a serious coupling relationship between deaerator level and steam pressure. Therefore, it may appear characteristic change due to the different operating conditions [2]. Industries use a PI control system to manage the deaerator. The PI control system appears many drawbacks, especially during disturbance on the system. Furthermore, the system must suit each instrument one by one. This causes the loss of the company both in terms of economic and material.

Some research on deaerator has been done such as Gomathy Sathiyamoorthy conducted a study on level control and pressure deaerator using four different controllers, namely PID controller, IMC controller, Fuzzy Logic controller, and Fuzzy-PID controller. The results showed that Fuzzy-PID controllers yields in better performance [3]. Peng Wang conducted a study on level control and pressure deaerator using PID Neural Network controller. The results expose that PID Neural Network produces better performance than PID because it can reduce to overshoot and settling time pressure and water level deaerator [1]. Adel Ben-Abdennourperformed a study on multivariable robust control. The authors demonstrated how to have more desirable performance and robustness in all the simulated cases. It was also shown to be fault accommodating [4].

In this research, we design a Model Reference Adaptive Control (MRAC) with MIT Rule method. The controller is applied in a multi input multi output (MIMO) 2x2 deaerator system. The controller parameters are adjusted to giving a desired closed-loop performance. The controller parameters are adjusted to obtaining the desired change of plant transfer function. Hereafter, its performance can be made similar to the reference model [6]. The parameters are adjusted using MIT Rule method. Comparative analysis of performance of pressure control system and deaerator levels with MRAC based on transient response character.

2. Research Method

2.1 Deaerator

A deaerator is a mechanical device that eliminates dissolved gases, such as carbon-dioxide and oxygen, from feedwater before it gets to a boiler and its pipeline [1]. Raw water will enter the demineralization plant. In the demineralization plant, the raw mineral water content will be removed so that it becomes demineralized(demin) water. The water that goes into the deaerator is sprayed into small grains, which aims to facilitate the separation process. The sprayed water will fall onto the tray, which serves as a heating medium and a filtration and facilitates the separation process is going. At the same time, steam is injected from the bottom of the deaerator to raise the water temperature of the demin to the boiling point of water. The increase in temperature causes a decrease in the solubility of the gases contained in the feed water. Water and steam that are entered simultaneously will collide on the tray. Water and steam mixed with this facilitate the process of separation of the gases. So with the mixing of this turbulent water resulted in the process of separation of the gases. The separated O2 gas will exit through the vent, while the O2-free water (feedwater boiler) enters the storage tank which will then obsess the plant. The Figure 1 shows the deaerator, which is used in the research.

Figure 1: Deaerator

The pressure and level model is based on Gomathy Sathiyamoorthy's research [3]. These pressure and level models are written in the following equations.

Pressure

$$P(s) = \frac{h_c}{\frac{(S_w m_w + S_s m_s)}{(S_v \dot{m}_v + S_f \dot{m}_f)}.s+1}\dot{m}_c - \frac{h_{mw}}{(S_w T \rho_w Z - S_w T Z \rho_s)s}\dot{m}_{mw} \quad (1)$$

Level

$$L(s) = \frac{h_{mw}}{(S_w T \rho_w Z - S_w T Z \rho_s)s}\dot{m}_{mw} \quad (2)$$

where:

$P(s)$ = pressure deaerator
$L(s)$ = water level deaerator
h_c = entalphy of condensate
h_{mw} = entalphy of makeup water
$\dot{m}_c$ = flow rate of condensate
$\dot{m}_{mw}$ = flow rate of makeup water
S_w = entropy of water
S_s = entropy of steam
S_v = entropy of vapor
S_f = entropy of flow out
m_w = water mass
m_s = steam mass
$\dot{m}_v$ = vapor mass
$\dot{m}_f$ = flow out mass
T = deaerator temperature
z = deaerator volume
ρ_w = water density
ρ_s = steam density

After the parameter values are inserted into the model above, then the transfer function models are written as follows:

$$\frac{P(s)}{\dot{m}_c(s)} = \frac{2585.89}{173.7471s+1} \quad (3)$$

$$\frac{P(s)}{\dot{m}_{mw}(s)} = \frac{125.86}{1410774.3s} \quad (4)$$

$$\frac{L(s)}{\dot{m}_{mw}(s)} = \frac{125.86}{-1410774.3s} \quad (5)$$

2.2 Decoupling

Based on equation (3), (4), and (5), deaerator is a MIMO control system. It has more than one number of controlled output variables and manipulated input variables. The MIMO system block diagram is shown in Figure 2 [7].

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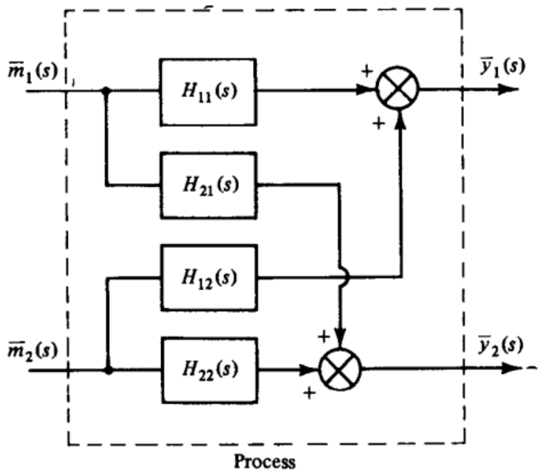

Figure 2: The MIMO system block diagram

The relationship between input and output of MIMO system is modeled by equation (6) and (7) [7].

Loop 1: $\overline{y_1}(s) = H_{11}(s)\overline{m_1}(s) + H_{12}(s)\overline{m_2}(s)$ (6)

Loop 2: $\overline{y_2}(s) = H_{21}(s)\overline{m_1}(s) + H_{22}(s)\overline{m_2}(s)$ (7)

The goal of all decoupling methods is the suppression of the undesirable interactions among input and output variables in order that each input affects only one controlled variable [5]. In the deaerator, the input level affects the output pressure. Therefore, the system requires a decoupler to reduce or even eliminate interactions between the two.The Figure 3 exhibits an MIMO 2x2 system process with one decoupler.

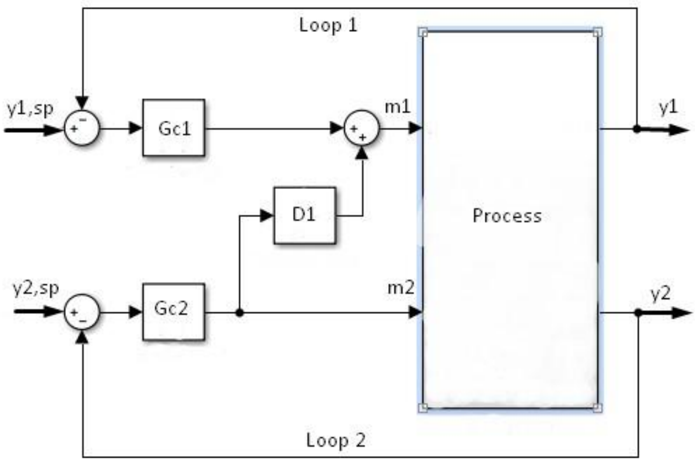

Figure 3: The block diagram of a 2x2 system process with one decoupler

In order to eliminate the effect of $\overline{m_2}$ on $\overline{y_1}$, so $(\overline{y_1} = 0)$ in equation (6). The function transfer equation of decoupler is writtenin the equation (8).

$$D_1(s) = -\frac{H_{12}(s)}{H_{11}(s)} \quad (8)$$

The decoupler equation of deaerator is shown by equation (9).

$$D(s) = -\frac{21867.81s + 125.86}{3.648107154.6s} \quad (9)$$

2.3 Model Reference Adaptive Control with MIT Rule

Model Reference Adaptive Control (MRAC) is a kind of adaptive control method based on the reference model, which is conductive for the control object to control its time-varying nonlinear characteristics [9]. In MRAC systems, that desired performance of the plant is expressed via a reference model, which gives the desired response to a command signal. A major reason of using MRAC is the elimination of relatively large overshoots and undershoots in the beginning of the transient, which may disturb the stable operation of the inverter in protecting the switching devices [10].

The adjustment mechanism technique in this MRAC is the MIT Rule. The MIT control strategy adjusts controller parameters online according to appropriate adaptive rules. The MIT rule approach aims to minimize the squared model cost function [11]. Because as the error function becomes minimum there will be perfect tracking between actual plant output (y) and reference model output (ym) [12]. The MIT Rule controller on a closed-loop system has an adjustable parameter θ. Parameter setting is done by minimizing the loss function J(θ), which is shown in the equation (10).

$$J(\theta) = \frac{1}{2}e^2 \qquad (10)$$

For a small J value, a parameter change in the negative gradient of J, according to equation (11).

$$\frac{d\theta}{dt} = -\gamma\frac{\partial J}{\partial\theta} = -\gamma e\frac{\partial e}{\partial\theta} \qquad (11)$$

From equation (3), (4), (5), then the plant is first order. The first order process system is shown by equation (12).

$$\frac{y(s)}{u(s)} = \frac{b}{s+a} \qquad (12)$$

The desired output of the system response corresponds to the model output according to (13).

$$\frac{y_m(s)}{u_c(s)} = \frac{b_m}{s+a_m} \qquad (13)$$

The controller parameters are shown in (14) and (15).

$$T = \frac{b_m}{b} \qquad (14)$$

$$S = \frac{a_m = a}{b} \qquad (15)$$

The equation of the controller signal is given in equation (16).

$$u = Tu_c - Sy \qquad (16)$$

The objective of MRAC will be achieved if equations (14) and (15) are met. Error is the difference between the system output shown in equation (17).

$$e = y - y_m \qquad (17)$$

Sensitivity derivatives are obtained by performing partial derivatives on errors of T and S parameters shown in equation (18) and (19).

$$\frac{\partial e}{\partial T} = \frac{b}{s+a+bS}u_c \qquad (18)$$

$$\frac{\partial e}{\partial S} = -\frac{b}{s+a+bS}y \qquad (19)$$

The updating equation of the controller parameters are shown in equation (20) and (21).

$$\frac{dT}{dt} = -\gamma\left(\frac{b}{s+a+bS}u_c\right)e \qquad (20)$$

$$\frac{dS}{dt} = \gamma\left(\frac{b}{s+a+bS}y\right)e \qquad (21)$$

The parameter approach is done because parameters a and b are unknown, so adjustment parameter parameter can be realized, as shown in (22). Parameter b can be absorbed into γ because parameters b and γ are constants [13].

$$s + a + bS = s + a_m \qquad (22)$$

Based on the statement, we find the equation (20) and equation (21) into equation (23) and (24).

$$\frac{dT}{dt} = -\gamma\left(\frac{1}{s+a_m}u_c\right)e \qquad (23)$$

$$\frac{dS}{dt} = \gamma\left(\frac{1}{s+a_m}y\right)e \qquad (24)$$

The first order MRAC block diagram of the MIT Rule is shown in Figure 4.

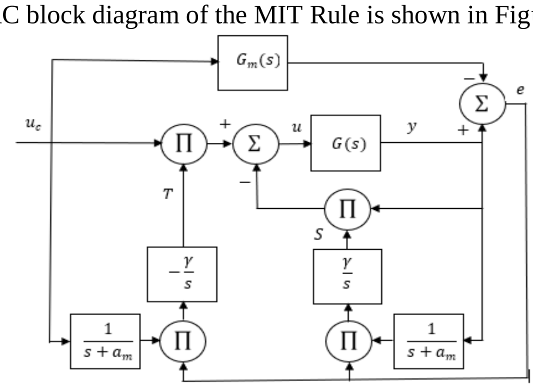

Figure 4: First-order MRAC block diagram with MIT Rule

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The reference model is used in the first order because the plant deaerator is first order. The equation of the model transfer function used has a time value of 143.75 seconds with the value a_m = 0.0069 for pressure and a time value of 84.7 seconds with the value a_m = 0.0118 for level.

Reference model pressure:

$$\frac{y_m}{u_c} = \frac{0{,}0069}{s+0{,}0069} \quad (23)$$

Reference model level:

$$\frac{y_m}{u_c} = \frac{0{,}0118}{s+0{,}0118} \quad (24)$$

3. Result and Analysis

Tests in this study were conducted in two stages of testing without disturbance and with disturbance. Testing without disturbance is performed to determine the system transient response and system performance in general. Testing with disturbance is done by giving increasing setpoint, decreasing setpoint, and disturbance of input step. It is done by comparing MRAC with PI controller. The PI controller used has K_p= 2.6x10^{-4} and K_i= 4x10^{-6} for pressure and K_p= -108 and K_i= -0.38for level which determined by trial and error method.

3.1 Testing without Disturbance

Pressure testing use setpoint of 11934.1 kg/m^2 with variation of γ_T and γ_S which determined by trial and error method. Pressure deaerator response is shown by Figure 5.

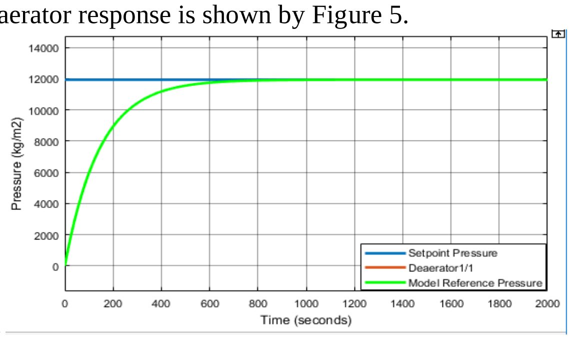

Figure 5: Deaerator pressure response γ_T = 5x10^{-5}danγ_S = 9x10^{-5}

Figure 5shows three graphs, which are blue chart shows setpoint pressure, green chart shows reference model, and red colour chart shows deaerator system response. The figures exhibits that the system response has followed the reference model well. The result of deaerator pressuretest is shown in Table 1.

Table 1: The performance of pressure deaerator

γ_T	γ_S	t_r (second)	t_s (second)	Error (kg/m^2)
5x10^{-1}	9x10^{-1}	318.4383	566.9599	3.638x10^{-12}
5x10^{-2}	9x10^{-2}	318.4384	566.9599	1x10^{-12}
5x10^{-3}	9x10^{-3}	318.4384	566.9598	7.276x10^{-12}
5x10^{-4}	9x10^{-4}	318.4384	566.9594	3.638x10^{-12}
5x10^{-5}	**9x10^{-5}**	**318.4409**	**566.9578**	**7.276x10^{-12}**

Based on Table 1, the smaller the adaptation value so the greater the rise time, while the settling time value is smaller. γ_T = 5x10^{-5} and γ_S = 9x10^{-5} are chosen because they yield the smallest settling time value.

Level testing use setpoint of 2.125 m. Deaerator level response is shown by Figure 6.

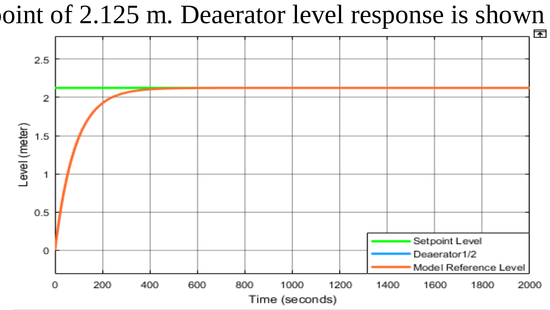

Figure 6: Deaerator level response γ_T = 9x10^{-1}danγ_S = 5x10^{-1}

Figure 6exposes 3 graphs are green chart shows setpoint pressure, red chart shows reference model, and blue chart shows deaerator system response. The figure exhibits that the system response has followed the reference model well. The performance of deaerator level test is shown in Table 2.

Table 2: The performance of deaerator level

γ_T	γ_S	t_r (second)	t_s (second)	Error (kg/m^2)
4x10^{-1}	**6x10^{-1}**	**186.1434**	**331.5292**	**6.973x10^{-7}**
4x10^{-2}	6x10^{-2}	185.5750	331.5444	6.973x10^{-6}
4x10^{-3}	6x10^{-3}	181.1307	331.7045	6.971x10^{-5}
4x10^{-4}	6x10^{-4}	169.6235	333.4026	6.957x10^{-4}
4x10^{-5}	6x10^{-5}	189.8860	351.9705	6.869x10^{-3}

Based on Table 2, the smaller the adaptation value so the greater the rise time value and the smaller the rise time value, except for γ_T = 4x10^{-5} and γ_S = 6x10^{-5}. It indicates the gain value are not suitable for the deaerator level system. While the smaller the adaptation value, the settling time value is smaller. γ_T = 4x10^{-1} and γ_S = 6x10^{-1} are chosen because they yield the smallest settling time value.

3.2 Increasing Set Point

In this test, set point value is increased by 500 kg/m^2 from the normal set point for pressure control and 0.1 m for level control when the system has reached stable condition in 1000 seconds. The result of the pressure system response is shown in Figure7.

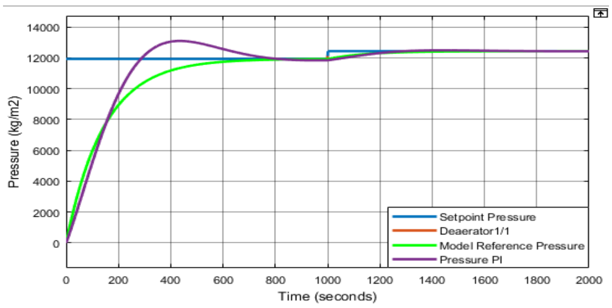

Figure 7: Deaerator pressure response with increasing setpoint

Figure 7 shows that the system with increasing setpoint, then the system will follow the given setpoint. The figure exposes that the system response has followed the reference model well.The performance of pressure test with increasing setpoint is shown in Table 3.

Table 3: The performance of deaerator pressure with increasing setpoint

Control System	t_r (second)	t_s (second)	Error (kg/m^2)
MRAC	386.2713	1.1044x10^3	1.762x10^{-8}
PI	226.1405	1.1363x10^3	4.469

Based on Table 3,the MRAC pressure response has a rise time value greater than PI with a difference of 160.1308 seconds. Whereas settling time and error of MRAC are smaller than PI with settling time difference of 31.9 seconds. In the deaerator, settling time takes precedence over the rise time because the system takes time to reach a fast steady state.Thus, the designed MRAC can work optimally for deaerator pressure with increasing setpoint compared to the PIcontroller.The result of the level system response shown in Figure 8.

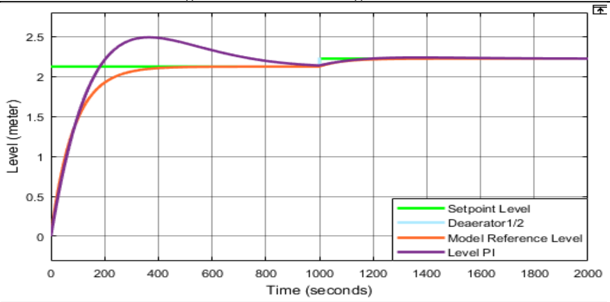

Figure 8: Deaerator level response with increasing setpoint

Figure 8 shows that the system with increasing setpoint, then the system will follow the given setpoint. The figure shows that the system response has followed the reference model well.The performance of level test with increasing setpoint is shown in Table 4.

Table 4: The performance of deaerator level with increasing setpoint

Control System	t_r (second)	t_s (second)	Error (kg/m^2)
MRAC	232.3819	1.069x10^3	6.61x10^{-7}
PI	149.6882	1.0641x10^3	5.571x10^{-4}

Based on Table 4,the MRAC level response has the rise time and settling time value greater than PI with the difference of 82.6937 seconds and 4.9 seconds. So that the designed MRAC system has not been able to overcome the setpoint level increase.

3.3 Decreasing Set Point

In this test, set point value decreased by 500 kg/m^2 from the normal set point for pressure control and 0.1 m for level control when the system has reached stable condition in 1000 seconds. The result of the system response shown in Figure 9 and Figure 10.

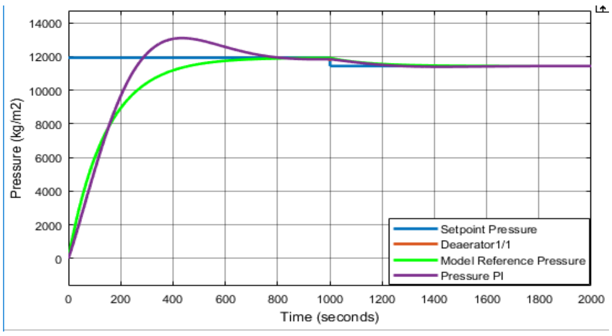

Figure 9: Deaerator pressure response with decreasing setpoint

Figure 9 exhibits that system with decreasing setpoint, then the system will follow the given setpoint. The figure shows that the system response has followed the reference model well.The performance of pressure test with increasing setpoint is shown in Table 5.

Table 5: The performance of deaerator pressure with decreasing setpoint

Control System	t_r (second)	t_s (second)	Error (kg/m^2)
MRAC	272.7786	1.1095x10^3	1.091x10^{-8}
PI	196.1806	1.0948x10^3	3.186

Based on Table 5,the MRAC pressure response has the rise time and settling time value greater than PI with the difference of 76.598 seconds and 14.7 seconds. So that the designed MRAC system has not been able to overcome the setpoint pressure decrease.The result of the level system response shown in Figure 10.

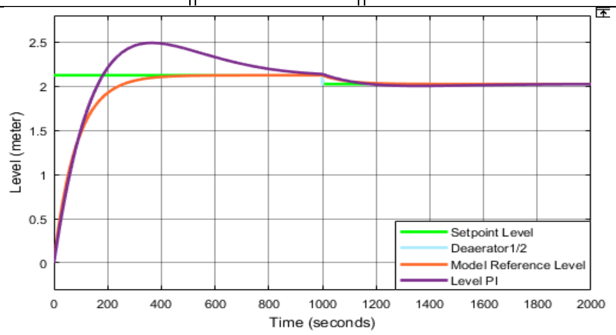

Figure 10: Deaerator level response with decreasing setpoint

Figure 10 shows that the system with decreasing setpoint, then the system will follow the given setpoint. The figures exposes that the system response has followed the reference model well.The performance of level test with decreasing setpoint is shown in Table 6.

Table 6: The performance of deaerator level with decreasing setpoint

Control System	t_r (second)	t_s (second)	Error (kg/m^2)
MRAC	156.6557	1.0766x10^3	7.245x10^{-4}
PI	124.9858	1.0868x10^3	7.377x10^{-4}

Based on Table 6,the MRAC level response has a rise time value greater than PI with a difference of 31.6699 seconds. Whereas settling time and error of MRAC are smaller than PI with settling time difference of 10.2 seconds. Thus, the MRAC is designed can work optimally for deaerator level with decreasing setpoint compared to the PI controller.

3.4 Testing with Disturbance

Testing for the effect of disturbance by giving a step signal disturbance of 800 kg/m^2 for pressure and 0.1 m for level when the system has reached stable condition in 1000 seconds. The results of the system response shown in Figure 11 and Figure 12.

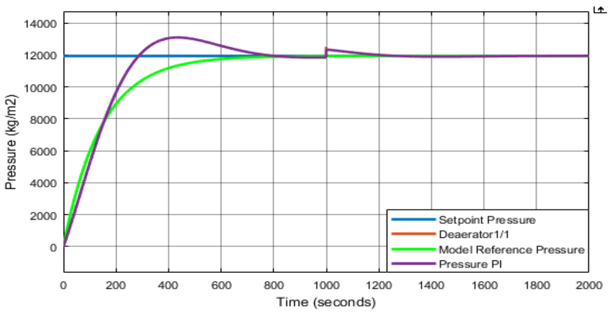

Figure 11: Deaerator pressure response with disturbance

Figure 11 shows that deaerator pressure system with disturbance has a spike in the system response and the system can return its value according to the setpoint value. The performance of pressure test with disturbance is shown in Table 7.

Table 7: The performance of deaerator pressure with disturbance

Control System	t_r (second)	t_s (second)	Error (kg/m^2)
MRAC	318.4369	1.003x10^3	1.637x10^{-11}
PI	210.3713	1.089x10^3	3.234

Based on Table 7,the MRAC pressure response has a rise time value greater than PI with a difference of 108.0656 seconds. Whereas settling time and error of MRAC are smaller than PI with settling time difference of 86 seconds. Thus, the designed MRAC is able to work optimally for deaerator pressure with disturbancecompared to the PI controller.

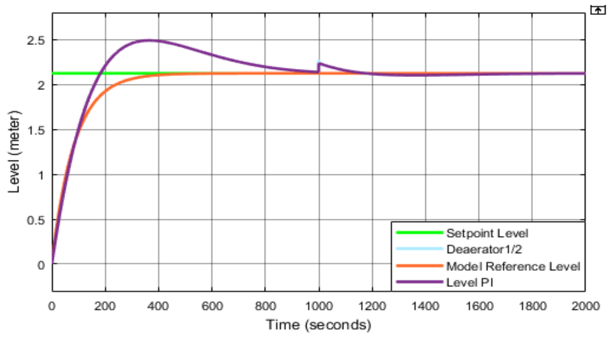

Figure 12: Deaerator level response with disturbance

Figure 12 shows that deaerator level system with disturbance has a spike in the system response and the system can return its value according to the setpoint value. The performance of level test with disturbance is shown in Table 8.

Table 8: The performance of deaerator level with disturbance

Control System	t_r (second)	t_s (second)	Error (kg/m^2)
MRAC	186.1434	1.002x10^3	6.694x10^{-7}
PI	136.5460	1.0837x10^3	7.179x10^{-4}

Based on Table 8,the MRAC pressure response has a rise time value greater than PI with a difference of 49.4974 seconds. Whereas settling time and error of MRAC are smaller than PI with settling time difference of 81.7 seconds. Thus, the MRAC is designed can work optimally for deaerator level with disturbance compared to the PI controller.

4. Conclusion

It has successfully designed the MRAC controller for water level and pressure control on the deaerator. The system is able to follow setpoints when the system is given disturbance and no. The smaller the adaptation value, the the greater the rise time value and the settling time value is smaller. The pressure testing with γ_T = 5x10^{-5}and γ_S = 9x10^{-5} yields the smallest settling time of 566.9578 secondsandγ_T = 4x10^{-1}and γ_S = 6x10^{-1}have the smallest settling time of 331.5292 seconds for level.The MRAC pressure deaerator system can work optimally compared to the PI controller when the setpoint increases because it has a smaller settling time with the difference of 31.9 seconds. Whereas the MRAC system has not been able to overcome the setpoint level increase because it has a greater settling time with the difference of 4.9 seconds. The MRAC pressure deaerator system has not work optimallycompared to the PI controller when the setpoint decreases because it has a greater settling time with the difference of 14.7 seconds. Whereas the MRAC system has been able to overcome the setpoint level decrease because it has a smaller settling time with the difference of 10.2 seconds. MRAC for pressure and deaerator level can work optimally compared to PI controller when given disturbance because it has smaller settling time with the difference 86seconds for pressure and 81.7 seconds for level.

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