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Fault-Tolerant Control Design in Scrubber Plant with Fault on Sensor Sensitivity

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Abstract The concept of fault-tolerant control has extensively been explored with various mapping of development. It starts from the system characteristic, the robustness of the controller, estimation methods and optimization, to the combination of the faults such that it can touch the true observed system. The mathematical concepts of the scrubber plant taking into account the pressure parameter along with sensing element and actuator are proposed. The data to construct the designs derive from the true values in one of Indonesian company. The performances coming from the simulations depict that the open- and closed-loop system could be the same as those of the real results. Furthermore, the observer is proposed to give the estimates of the states of ($\hat{x}$) and ($\hat{f}_s$) showing the positive trace on the set-point of the residual fault followed by designing the fault-tolerant control with sensor fault on sensitivity. The scenarios are to give the lack of reading in sensor with 70% and 85% sensitivity and those are contrasted to the system without FTC (only PI controller). The yields portray that the system with FTC could deal with those sensor fault scenarios while its counterpart cannot draw the faulty performance instead of tracking the set-point. The next project associated with this paper is also mentioned in the last section.

Keywords Fault-tolerant control, Estimation method, Sensor fault, Scrubber plant.

1. Introduction / Background

The early design of proposing fault-tolerant control (FTC) in the late 20th century was triggered by the failure of switching in telephone networks being aggravated with aircraft crashed [1]. Moreover, fault diagnostics scheme in non-linear stochastic system with sensor fault along with PID-feedback and Monte-Carlo appeared in just a decade after [2] and [3]. While the identification is vital [4], the importance for self-tracking to the faults was discussed in [5] and [6], along with additional of switching scenario in the second compared to the first [7]. Beyond that, the distribution of the FTC with certain adaptive method, robust Pareto estimation and various estimation methods being compared were suggested in [8], [9], and [10] in turn, making this research interest becoming more dynamic and extensive to the industrial system. The scenarios of observer and decoupling control along with the condition of two faults both on sensor and actuator were written in [11] and [12] whereas the same condition with a tolerance measure and H_∞-based observer was carried out by [13] and [14], comprising three patterns of faulty states, either sensor or actuator and their combination. As for the paper, the design of two faults would be in the next project along with scenario of unobservability on the system. In terms of application, many objects with discrete-time design are suitable for this research area as mentioned in [15] and [16]. Having said the development and advanced scenario with respect to fault-tolerant control, the general overview has been well-written in [17] saying the comprehensive explanation on it. As regards the paper, the mathematical and concept design of the plant was proposed in [18] such that it can be used to approach the true system. The theoretical and mathematical design of the system being implemented constitute from [19] and [20] respectively. As mentioned in the preceding paragraph regarding the next research, the concept would be aided by the following research to deal with unobservability.

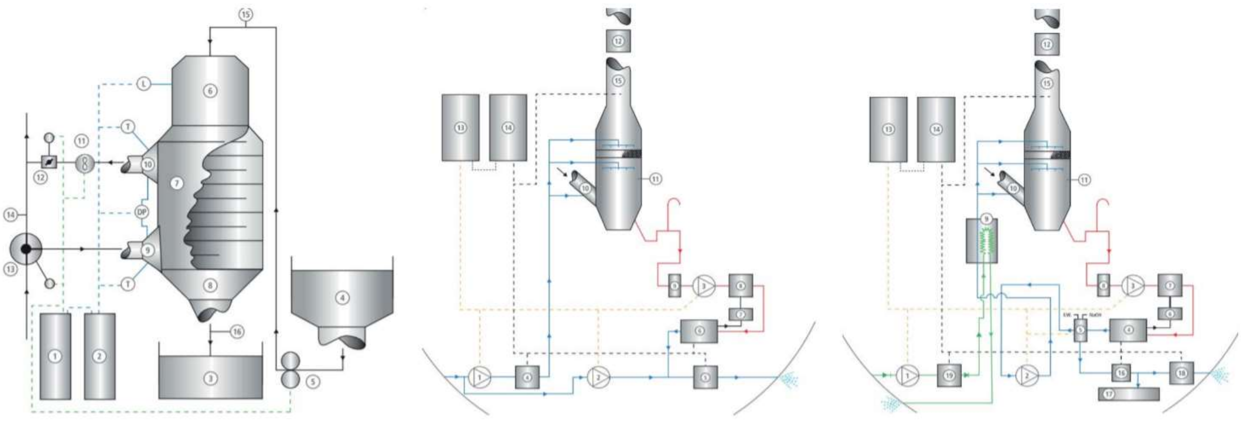
2. Proposed Design

This section enlightens the mathematical models of control system focusing on pressure parameter applied in the Scrubber with analytics of the plant itself, the transmitter, and the control valve. Furthermore, the controller, the estimation design and the reconfigurable in the fault-tolerant control are also presented as the integrated system.

A. Mathematical Model of Plant

The scrubber (V-100) plant in this research is according to real condition in one of the oil and gas Indonesian companies due to the existing of sensor fault. There are two sort of choices, the wet- and dry-scrubber. As regards the first, the direct contact between the polluted gas and the scrubbing liquid is situated by both pool (absorbing) and sprayer (dissolving) of liquid. Dry scrubber also being used in this paper as shown in Fig. (1) is to spray granulate absorbent such that it vanishes the sulfur dioxide. The mathematical model is initiated by formulating the mass balance [17]-[20] such that,

$$\frac{d}{dt}(\rho_l V_l + \rho_g V_g) = q_i - q_{o(l)} - q_{o(g)} \tag{1}$$



(a) (b) (c)

Figure 1: (a). System of dry scrubber; *(b). Scrubber open-loop design*; *(c). Scrubber closed-loop design* [18]

Table 1: Description of instruments in figure (1) as stated in [18]

No.	Dry Scrubber	Open-loop	Closed-loop	Hybrid
1	Control cabinet	Salt wash water pump	Cooler sea-water pump	
2	Monitoring cabinet	Effluent dilution pump	Wash water supply pump	
3	Reaction product	Effluent water discharge pump	Effluent water re-circulation pump	
4	Granulate storage	Salt wash water monitor	Oil & soot separator	
5	Monitoring Cabinet	Effluent water monitoring	Alkali (NaOH) Unit	
6	Granulate silo	Oil & soot separator	EGC residue tank	
7	Scrubber reactor	EGC residue tank	Sludge separator	
8	Reaction product	Sludge separator	Reareation unit	
9	Exhaust inlet	Reareation unit	Wash water cooler	
10	Exhaust outlet	Exhaust gas inlet	Exhaust gas inlet	Combination of open-loop and closed-loop system
11	Exhaust fan	Scrubber	Scrubber	
12	Isolation valve	Exhaust gas inlet	Exhaust fan	
13	3-way inlet/Bypass valve	Control fan	Control cabinet	
14	Exhaust bypass manifold	Monitoring & alarm cabinet	Monitoring & alarm cabinet	
15	Granulate absorption inlet	Exhaust gas outlet	Exhaust gas outlet	
16	Reaction product outlet		Bleed-off treatment unit	
17			Holding tank	
18			Effluent water monitoring	
19			Wash water cooling monitoring	

and the more complex equation is written as follows,

$$\frac{d}{dt}(\rho_l V_l + \rho_g V_g) = V_l\frac{\partial \rho_l}{\partial t} + \rho_l\frac{\partial V_l}{\partial t} + V_g\frac{\partial \rho_g}{\partial t} + \rho_g\frac{\partial V_g}{\partial t} \tag{2}$$

Where the variables of q_i, ρ, V and q_o are inlet flow (kg/s), density (kg/m^3), volume (m^3) and outlet flow with respect to certain gas (g) and liquid (l). The energy balance (ΔE) should also be considered as a whole system, therefore,

$$E_{21} = (E_{k_2} - E_{k_1}) + (E_{p_2} - E_{p_1}) + (U_2 - U_1) \tag{3a}$$

$$\Delta E = \Delta E_k + \Delta E_p + \Delta U \tag{3b}$$

which can be written as Eq. (4a) along with its flow rate (4b),

$$Q - W = \Delta E_k + \Delta E_p + \Delta U \tag{4a}$$

$$\dot{Q} - \dot{W} = \frac{d}{dt}(\Delta E_k + \Delta E_p + \Delta U) \tag{4b}$$

From Eqs. (3a) and (3b) to Eq. (1), the equation is then formulated as follows,

$$\frac{d}{dt}E = E_i - E_o + Q \rightarrow E = \rho_g h_g V_g + \rho_l h_l V_l \tag{5a}$$

$$\frac{d}{dt}E = q_i h_i - q_{o(l)} h_{o(l)} - q_{o(g)} h_{o(g)} \tag{5b}$$

and the equations for each liquid and gas inside the scrubber are given below in Eqs. (6a) and (6b) taking into account the inlet ($\dot{m}_i$) and outlet ($\dot{m}_o$) flow along with their enthalpy (input-output) variable h_i (J/kg) and h_o (J/kg), such that

$$\frac{d}{dt}(\rho_l h_l V_l) = \rho_{i(l)} h_{i(l)} \dot{m}_{i(l)} - \rho_{o(l)} h_{o(l)} \dot{m}_{o(l)} \tag{6a}$$

$$\frac{d}{dt}(\rho_g h_g V_g) = \rho_{i(g)} h_{i(g)} \dot{m}_{i(g)} - \rho_{o(g)} h_{o(g)} \dot{m}_{o(g)} \tag{6b}$$

Furthermore, pressure balance is then also considered as the sensing element is pressure itself such that the mathematical theory is proposed in the following,

$$\frac{d}{dt}p = \frac{\rho h g}{A}(\dot{m}_i - \dot{m}_o) \tag{7a}$$

$$\frac{d}{dt}p = \frac{\rho_i h_i g_i \dot{m}_i}{A} - \frac{\rho_{o(g)} h_{o(g)} g_{o(g)} \dot{m}_{o(g)}}{A} \tag{7b}$$

where p is pressure (Psi) with $\dot{m}_{o(g)}$ equals to $k\sqrt{p}$ which should be linearized applying Taylor series by avoiding the higher-order of the equation Eq. (9) resulting Eq. (8).

$$k\sqrt{p} = k\sqrt{p_o} + \frac{k}{2\sqrt{p_o}}(p - p_o) \tag{8}$$

By substituting the result above, Eq. (7b) is then transformed to Eq. (11) after being altered into Laplace transform and some algebra. The transfer function of scrubber is described in Eq. (12) with p_o, K_s and τ_s are pressure output, gain and the time constant of scrubber. Those parameters are obtained from the measurement with control as depicted in Fig. (2)

$$k\sqrt{p} = k\sqrt{p_o} + \left.\frac{d(k\sqrt{p})}{dp}\right|_{p=p_o}(p - p_o) + \left.\frac{d^2(k\sqrt{p})}{dp^2}\right|_{p=p_o}\frac{(p-p_o)^2}{2!} + \left.\frac{d^3(k\sqrt{p})}{dp^3}\right|_{p=p_o}\frac{(p-p_o)^3}{3!} + \cdots \tag{9}$$

$$\frac{dp}{dt} + \frac{\rho_{o(g)} h_{o(g)} g}{A} \left(k\sqrt{p_o} + \frac{k}{2\sqrt{p_o}} (p - p_o) \right) = \frac{\rho_i h_i g \dot{m}_i}{A} \tag{10}$$

$$P(s) \left(\frac{2A\sqrt{p_o}}{\rho_{o(g)} h_{o(g)} gk} s + 1 \right) = \left(\frac{2\sqrt{p_o}}{k} \right) \frac{\rho_i h_i g}{\rho_{o(g)} h_{o(g)} g} \dot{M}_i(s) \rightarrow \text{divided by } \frac{\rho_{o(g)} h_{o(g)} g}{A} \left(\frac{k}{2\sqrt{p_o}} \right) \tag{11}$$

$$\frac{P(s)}{\dot{M}_i(s)} = \frac{\left(\frac{2\sqrt{p_o}}{k} \right) \frac{\rho_i h_i g}{\rho_{o(g)} h_{o(g)} g}}{\frac{2A\sqrt{p_o}}{\rho_{o(g)} h_{o(g)} gk} s + 1} := \frac{K_s}{\tau_s s + 1} \tag{12}$$

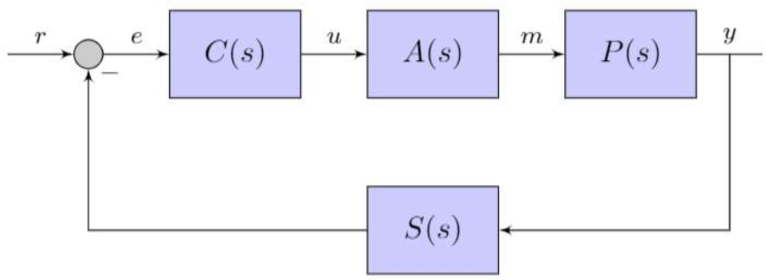


Figure 2: A loop of control system with controller (C), actuator (A), plant (P) and sensing element (S)

B. Mathematical Model of Actuator and Sensing

Pressure transmitter (PT-0105) with diaphragm-based is implemented so that what is measure will be transferred into 4-20 mA (DC). Its mathematical design can be approached as given below,

$$G_t(s) = \frac{K_t}{\tau_t s + 1} \rightarrow K_t = \frac{O_{\max} - O_{\min}}{I_{\max} - I_{\min}} \tag{13}$$

Where (K_t) is gain transmitter with the span comparison from output over input while (τ_t) is the time constant of the transmitter. With respect to actautor being used, it is PV-0105 to maintain the flow as the set point. The control valve gain K_v (mmscfd/mA) is constructed from $\mathcal{G}_v$ (mmscfd/psi) and $\mathcal{G}_{\text{I/P}}$ which is converting 4-20 (mA) to pneumatic signal 3-15 (psi) which can be seen in Eq. (14)

$$\mathcal{G}_v = \frac{\text{span output}}{\text{span input}} \; ; \; \mathcal{G}_{\text{I/P}} = \frac{\text{span output}}{\text{span input}} \tag{14}$$

such that,

$$K_v = \mathcal{G}_v \cdot \mathcal{G}_{\text{I/P}} \tag{15}$$

The time constant of control valve is then generated in Eq. (16). T_v is full stroking time with $\frac{Y_c}{C_v}$, Y_c is the factor stroking time and R_v is the constant between inherent-time over stroke, constituting either 0.03 or 0.01 for diaphragm- or piston-based actuator while ΔV is the change fraction, and the equation becomes,

$$\tau_v = T_v(\Delta V + R_v) \rightarrow \Delta V = \frac{q_{\max} - q_{\min}}{q_{\max}} \tag{16}$$

and,

$$G_v = \frac{K_v}{\tau_v s + 1} \equiv \frac{M_i(s)}{U(s)} \tag{17}$$

The transfer function of actuator is then written as Eq. (17) which equals to the manipulated variable of $\dot{M}_i$ (Laplace) over signal input U.

C. Mathematical Model of Controller

The transient response is the key to yield the best performance so that it should be inside the good threshold. There are four major analyses presented in the following equations, where $\omega_d = \omega_n\sqrt{1-\zeta^2}$ and $\sigma = \zeta\omega_n$. The t_r, t_p, t_s refer to rise-time, peak-time and settling-time along with maximum overshoot M_P which are clearly depicted in Fig. (4), therefore

$$t_r = \frac{\pi-\beta}{\omega_d}(s) \rightarrow \beta = \tan^{-1}\frac{\omega_d}{\sigma}(\text{rad}) \quad (18a)$$

$$t_p = \frac{\pi}{\omega_d}(s) \quad (18b)$$

$$t_s = \frac{4}{\sigma}(s) \rightarrow 2\% \qquad t_s = \frac{3}{\sigma}(s) \rightarrow 5\% \quad (18c)$$

$$M_p = e^{-\left(\frac{\sigma}{\omega_d}\right)\pi}\% \quad (18d)$$

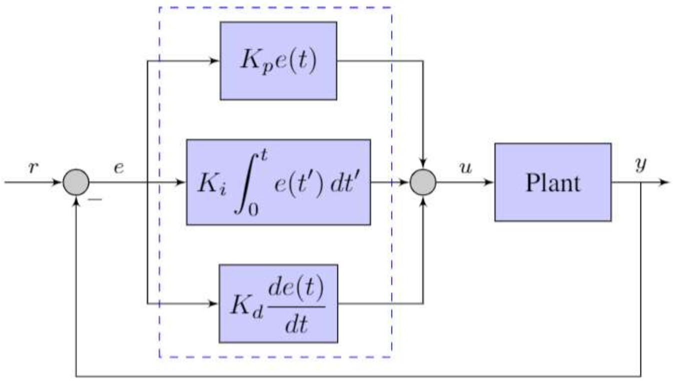


Figure 3: Scheme of PID controller

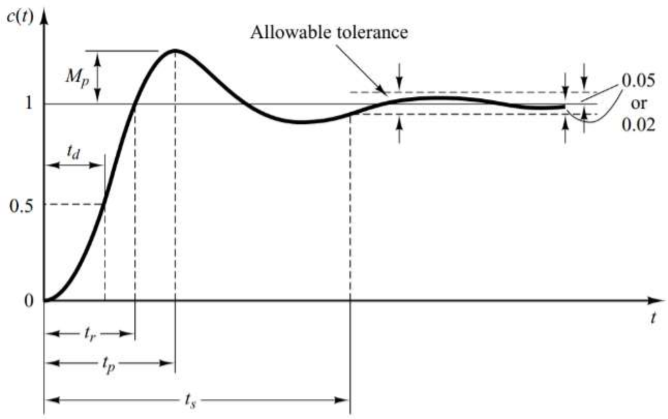


Figure 4: Analysis of transient response [20]

The controller being implemented in this system is PI with scenario as highlighted in Eq. (19), detailing K_p, $K_i = \frac{K_p}{T_i}$ and $K_d = K_p T_d$. Moreover, the success of the performance is determined by generating the best fit for these gain

$$u(t) = K_p\left[e(t) + \frac{1}{T_i}\int_0^{t'} e(t')\,dt' + T_d\frac{de(t)}{dt}\right] \quad (19)$$

D. Mathematical Model of Estimator

The basic dynamical control system is illustrated in these two equations,

$$\dot{x} = Ax + Bu \tag{20a}$$

$$y = Cx + \mathcal{F} f_s \tag{20b}$$

The matrices of $A, B, C, \mathcal{F}$ is for the system, input, output and the fault affected by two parameters, pressure and the inlet flow acting as the state of the system x. This matrix is built from two transfer functions of both plant (scrubber) and actuator (PV-0105) as clearly mentioned in Eqs. (12) and (17) followed by inverse-Laplace,

$$P(s)(\tau_s s + 1) = K_s \dot{M}_i(s) \tag{21a}$$

$$sP(s) = -\frac{P(s) + K_s \dot{M}_i(s)}{\tau_s} \tag{21b}$$

$$\frac{dp(t)}{dt} = -\frac{p(t) + K_s \dot{m}_i(t)}{\tau_s} \tag{21c}$$

and,

$$\dot{M}_i(s)(\tau_v s + 1) = K_v U(s) \tag{22a}$$

$$s\dot{M}_i(s) = -\frac{\dot{M}_i(s) + K_v U(s)}{\tau_v} \tag{22b}$$

$$\frac{d\dot{m}_i(t)}{dt} = -\frac{\dot{m}_i(t) + K_s u(t)}{\tau_v} \tag{22c}$$

After computing these two formulas, the whole state-space can be arranged as given in Eq. (23),

$$\frac{d}{dt}\begin{bmatrix} p(t) \\ \dot{m}_i \end{bmatrix} = \begin{bmatrix} -\frac{1}{\tau_s} & \frac{K_s}{\tau_s} \\ 0 & -\frac{1}{\tau_s} \end{bmatrix} \begin{bmatrix} p(t) \\ \dot{m}_i \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{K_s}{\tau_s} \end{bmatrix} u(t) \quad \Bigg| \quad y = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} p(t) \\ \dot{m}_i \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} f_s \tag{23}$$

To compensate the sensor fault as design in this paper, it is required to modify the state-space by inserting a new variable of $\dot{\xi}$ as in Eq. (24) to the original states resulting the Eq. (25), therefore,

$$\dot{\xi} = \Phi(y - \xi) = \Phi C x + \Phi \mathcal{F} f_s - \Phi \xi \tag{24}$$

such that,

$$\begin{bmatrix} \dot{x} \\ \dot{\xi} \end{bmatrix} = \begin{bmatrix} A & \mathbf{O} \\ \Phi C & -\Phi \end{bmatrix} \begin{bmatrix} x \\ \xi \end{bmatrix} + \begin{bmatrix} B \\ \mathbf{O} \end{bmatrix} u + \begin{bmatrix} \mathbf{O} \\ \Phi \mathcal{F} \end{bmatrix} f_s \quad \Bigg| \quad y_e = \begin{bmatrix} \mathbf{O} & I \end{bmatrix} \begin{bmatrix} x \\ \xi \end{bmatrix} \tag{25}$$

Those two modified equations above can be simplified into these two equations Eq. (26) respectively,

$$\dot{x}_e = A_e x_e + B_e u + \mathcal{F}_e f_s \quad \Big| \quad y_e = C_e x_e \tag{26}$$

These formulas are applied in the observer in estimating the state ($\dot{\hat{x}}_e$), fault ($\hat{f}_s$) and output ($\hat{y}_e$) as highlighted in Eqs. (27a), (27b), and (27c), constituting

$$\dot{\hat{x}}_e = A_e \hat{x}_e + B_e u + \mathcal{F}_e \hat{f}_s + L_x (y - \hat{y}) \tag{27a}$$

$$\hat{f}_s = L_f (y - \hat{y}) \tag{27b}$$

$$\hat{y}_e = C_e \hat{x}_e \tag{27c}$$

where the matrices then are written in Eq. (28)

$$\begin{bmatrix}\dot{\hat{x}}_e \\ \hat{f}_s\end{bmatrix} = \begin{bmatrix}A_e & \mathbf{O} \\ \mathbf{O} & \mathbf{O}\end{bmatrix}\begin{bmatrix}\hat{x}_e \\ \hat{f}_s\end{bmatrix} + \begin{bmatrix}B_e \\ \mathbf{O}\end{bmatrix} u + \begin{bmatrix}L_x \\ L_f\end{bmatrix}(\Delta y) \quad \Bigg| \quad y_e = \begin{bmatrix}C_e & \mathbf{O}\end{bmatrix}\begin{bmatrix}\hat{x}_e \\ \hat{f}_s\end{bmatrix} \tag{28}$$

along with its simplified equations as Eqs. (29a), (29b),

$$\dot{x}_\gamma = A_\gamma x_\gamma + B_\gamma u + K_\gamma f_s \tag{29a}$$

$$\hat{y}_e = C_\gamma x_\gamma \tag{29b}$$

E. Fault-tolerant Control Design

The fault-tolerant control (FTC) comprising two most renowned designs, passive-FTC and active-FTC, guarantees the system to accommodate the failures. The high performance along with its reliability are the aims to formulate this mechanism. The robust fixed-controller with apriori faults accounts for the passive-FTC while its counterpart is supposed to be more dynamic to the faulty states such that it maintains throughout the stability system. With respect to the scheme, fault detection diagnosis (FDD) along with reconfigurable control exist in the active-FTC whereas the passive-FTC does not require those [17]. From Fig. (5), it can be written that,

$$y_m = y + f_s \tag{30}$$

$$y_t = y_m - \hat{f}_s \tag{31}$$

and $e = r - y_t$ where r, e, and u are the reference signal, the error, and the control signal in turn. The y_m is the measured variable which is the addition of the true value and the faulty state f_s. The y_t would be returned compared to the reference

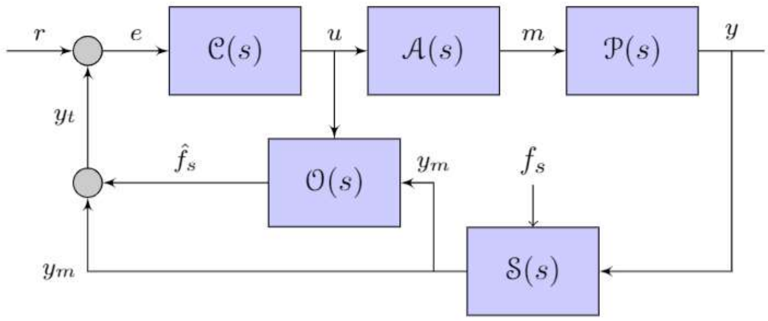


Figure 5: Scheme of disturbance observer

3. Results & Discussion

A. Mathematical Model of Plant

The volume (V), diameter (d), height (H) and the pressure set of the scrubber are 2.5 m^3, 1.07 m, 2.4 m and 24 bar. The specific gravity of the liquid (γ_l) and gas (γ_g) are 0.726 and 1.173. The density of input (ρ_i) and output (ρ_o) flow along with their enthalpy (h_i) and (h_o) are 5.2 kg/m^3, 4.9 kg/m^3, 4.9 J/kg, and 4.1 J/kg in turn. k and p_o equal to 1 and 348.091. In terms of sensing element and actuator, G_t is 1 and $\mathcal{G}_{\mathrm{I/P}}$ accounts for 3-15 psi over 4-20 mA while the span of gas makes up 12-16 mmscfd. Y_c and C_v are 0.68 and 117 respectively. As for controller, K_p and T_i are 0.1396 and 0.3294.

$$A_\gamma = \begin{bmatrix} a & b & 0 & 0 & 0 \\ 0 & c & 0 & 0 & 0 \\ d & 0 & z & 0 & d \\ 0 & d & 0 & z & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, B_\gamma = \begin{bmatrix} 0 \\ 0.9920 \\ 0 \\ 0 \\ 0 \end{bmatrix}, C_\gamma = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

with $a = -5.025$, $b = 277.45$, $c = -3.968$, $d = 1$ and $z = -1$.

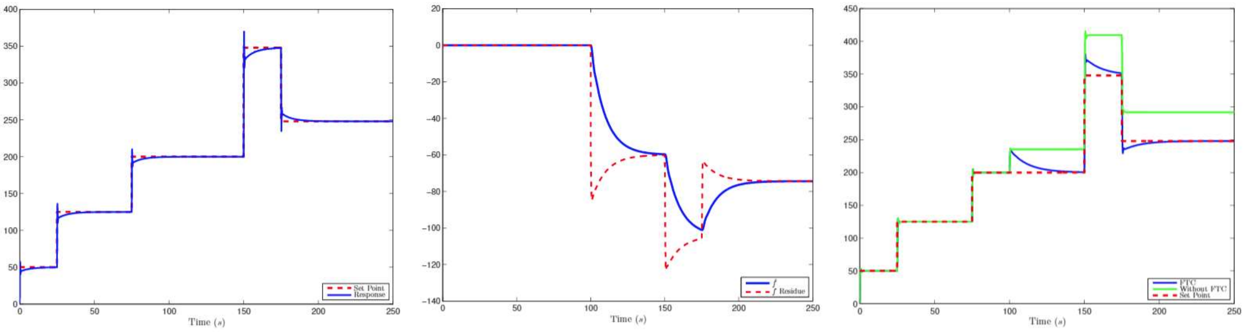
B. Numerical Analysis

The test of open-loop scheme depicts the rewarding results in approaching the true system, constituting just over 1% error in average as illustrated in Table. 2. The closed-loop scenario in Fig. (6a) also indicates the tracking with slight overshoot while some rising set-point comes. This implies that the gain of the controller suits the system. Furthermore, the sensing element is supposed to be failure to draw the true system related to sensitivity error, comprising 85% in certain iteration step

Table 1: Design of open-loop system compared to the real value

Real	Simulation	Error (%)
346.113	349.6	1.01
347.235	351	1.08
348.091	352.1	1.15
346.702	350.2	1.01
344.805	347.9	0.90
345.921	349.9	1.15
347	350.7	1.07
345.065	349	1.14
342.186	345.1	0.85
344.237	347.7	1.01

A faulty pattern is simulated in Fig. (6c) which conclude that in the 100^{th}-step the FTC could deal with the faulty states leading to trace the set-point whilst the system without FTC is unable to handle this situation and keeps performing the wrong tracking. The greater the faulty scenario will be, the greater the fault is created by the only-controller system. The ability of balancing the system constitutes FTC the method which is robust and preferable in industrial system if the faults on either a sensor or actuator, even both, are occurred either in different time or simultaneously. Finally, Fig. (6b) infers the tracking from observer in terms of fault compared to the residual fault.



(a) (b) (c)

Figure 5: (a). Closed-loop with PI; (b). $\hat{f}$ *against f residue; (c). 85% sensitivity*

4. Conclusion

Mathematical designs from, sensor, actuator, to scrubber have been proposed along with observer and fault-tolerant control. Closed-loop system indicates the rewarding performance to trace the set-point. The performance under FTC could deal with sensor fault in 100^th iteration. It could follow the set-point (blue) compared to that of without FTC (PI only) which keep demonstrating the faulty values with two different scenarios of faulty sensitivity. The created observer also emphasizes the rewarding results by the ability of fault estimation to cope with the f residue. The following project is to place the faults on both actuator and sensor along with some unobservability scenario

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