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by Ir Tamaji

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OUTPUT FEEDBECK FUZZY CONTROLLER DESIGN OF POWER SYSTEM STABILIZER FOR SINGLE MACHINE INFINITE BUS SYSTEM

by
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ABSTRACT - The Single Machine Infinite Bus (SMIB) is a non linear model of power system generation. The instability of SMIB is avoided by using the Power system stabilizer (PSS). The PSS is used to damp the mechanic electro oscillation in electricity power system. There are some methods of PSS control design are adaptive control, robust control, fuzzy controller and so on. Here, we design the PSS controller by using the output feedback fuzzy controller. At the first time, we build the Takagi-Sugeno fuzzy model, the second step is determining the output feedback controller based on the Ruth-Hurwitz criteria, and finally we do simulation to see the performance of PSS.

Keywords : SMIB, PSS, fuzzy controller, output feedback.

I. INTRODUCTION

In power system generation, power system stabilizer (PSS) is use to damp the mechanic electro oscillation. This oscillation is a disturbance of system. Some disturbances are due to continuing variation of power, changing the set point and others. Some methods of PSS design controller are direct feedback linearization [1, 2], adaptive control and robust control beside that fuzzy logic is influence to increase the performance of PSS.

In this paper, we design the output feedback controller of single machine infinite bus (SMIB). The mathematical model of SIMB system is non linear system [1, 3]. To design the controller of this PSS, at the first time, we change the mathematical model of SIMB into fuzzy model T-S, after that we define the fuzzy output feedback controller, we determine the output feedback gain base on the Ruth-Hurwitz criteria, and finally we make simulation to analyze the performance of PSS.

II. SMIB Fuzzy Model

The generating power system is a non linear system [1, 3] as follows

$$\begin{aligned}
\dot{\delta} &= -\omega_0\omega \\
\dot{\omega} &= (T_m - E_q^{'}I_q - (x_q - x_d^{'})I_dI_q)/M \\
\dot{E}_q^{'} &= (-E_q^{'} - (x_q - x_d^{'})I_d + E_{fd})/T_{d0}^{'} \\
\dot{E}_{fd}^{'} &= \frac{K_E}{T_E}(V_{ref} - V_T + u_{pss}) - \frac{1}{T_E}E_{fd}
\end{aligned} \tag{1}$$

The state variable δ, ω, $E_q^{'}$, $E_{fd}^{'}$ is angle, angular velocity, induced EMF proportional to field current and generator field voltages, respectively.

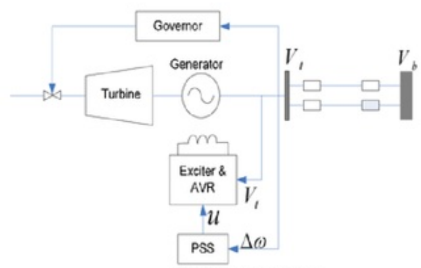

Figure 1. SMIB [4]

We know that

$$P_e = \frac{E_q^{'}V_s}{x_{dc}^{'}}Sin\delta; \tag{2}$$

$$Q = \frac{E_q^{'}V_s}{x_{dc}^{'}}Cos\delta - \frac{V_s^2}{x_{dx}^{'}}; \tag{3}$$

$$V_T = \sqrt{V_d^2 + V_q^2}$$

$$V_d = -X_eI_q + V_sSin\delta \tag{4}$$

$$V_q = X_eI_d + V_sCos\delta \tag{5}$$

By substitute Equation (2) and (3) into Equation (4) and (5) we obtain

$$V_d = -X_eI_d + \frac{P_ex_{dc}^{'}}{E_q^{'}};$$

$$V_q = X_eI_q + \left(Q + \frac{V_s^2}{x_{dx}^{'}}\right)\frac{x_{dc}^{'}}{E_q^{'}};$$

Or

$$I_d = \frac{P_e x'_{dc}}{E'_q X_e} - \frac{V_d}{X_e};$$

$$I_q = \frac{V_q}{X_e} - \left(Q + \frac{V_s^2}{x'_{dc}}\right)\frac{x'_{dc}}{E'_q X_e}$$

Because the system is non linear and we want to build the Takagi-Sugeno fuzzy model, then we arrange Equation (1) become

$$\dot{\delta} = \omega_0 \omega$$

$$\dot{\omega} = \frac{T_m}{M\delta}\delta - E'_q \frac{I_q}{M}\left[1 + (x_q - x'_d)\frac{I_d}{E'_q}\right] \quad (6)$$

$$\dot{E}'_q = -\left[\frac{1}{T'_{d0}} + (x_q - x'_d)\frac{I_d}{E'_q T'_{d0}}\right]E'_q + \frac{E_{fd}}{T'_{d0}}$$

$$\dot{E}'_{fd} = \frac{K_E}{T_E E'_q}(V_{ref} - V_T)E'_q - \frac{1}{T_E}E_{fd} + u_{pss}\frac{K_E}{T_E}$$

We can write Equation (6) as state space system as follows:

$$\begin{bmatrix} \dot{\delta} \\ \dot{\omega} \\ \dot{E}'_q \\ \dot{E}'_{fd} \end{bmatrix} = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ \frac{T_m}{M\delta} & 0 & -S_1 & 0 \\ 0 & 0 & -S_2 & \frac{1}{T'_{d0}} \\ 0 & 0 & S_3 & -\frac{1}{T_E} \end{bmatrix} \begin{bmatrix} \delta \\ \omega \\ E'_q \\ E'_{fd} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{K_E}{T_E} \end{bmatrix} u_{pss} \quad (7)$$

Where

$$S_1 = \frac{I_q}{M}\left[1 + (x_q - x'_d)\frac{I_d}{E'_q}\right]$$

$$S_2 = \left[\frac{1}{T'_{d0}} + (x_q - x'_d)\frac{I_d}{E'_q T'_{d0}}\right]$$

$$S_3 = \frac{K_E}{T_E E'_q}(V_{ref} - V_T)$$

The state space system in Equation (7) can be written in general form

$$\dot{x} = Ax + Bu$$

Where

$$x = \begin{bmatrix} \delta & \omega & E'_q & E'_{fd} \end{bmatrix}^T; \quad A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ \frac{T_m}{M\delta} & 0 & -S_1 & 0 \\ 0 & 0 & -S_2 & \frac{1}{T'_{d0}} \\ 0 & 0 & S_3 & -\frac{1}{T_E} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & \frac{K_E}{T_E} \end{bmatrix}; \qquad u = u_{pss}$$

In this problem, the fuzzy variable are P, Q, X_e, the variable

P: active power loading; Q: reactive power loading; X_e : equivalent tie-line reactance

where

$$P \in \left[P^- \quad P^+\right] \; Q \in \left[Q^- \quad Q^+\right] \; X_e \in \left[X_e^- \quad X_e^+\right]$$

such that we can derive the fuzzy rules as follows:

Rule Model 1

$IF.....P(t) is..P^- AND...Q(t) is..Q^- AND...X_e(t) is..X_e^-$

$THEN....\dot{x}(t) = A_1 x(t) + Bu(t)$

$y(t) = Cx(t)$

Rule Model 2

$IF.....P(t) is..P^- AND...Q(t) is..Q^- AND...X_e(t) is..X_e^+$

$THEN....\dot{x}(t) = A_2 x(t) + Bu(t)$ ....

$y(t) = Cx(t)$

Rule Model 8

$IF.....P(t) is..P^+ AND...Q(t) is..Q^+ AND...X_e(t) is..X_e^+$

$THEN....\dot{x}(t) = A_8 x(t) + Bu(t)$

$y(t) = Cx(t)$

The member function of P, Q, X_e can be represented as figure 2.

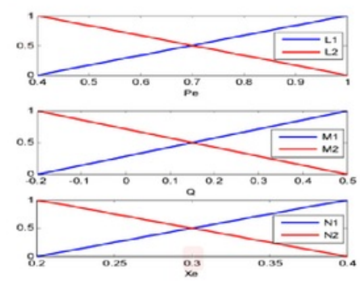

Figure 2. Member Function

The member functions of P are $L_1 = \frac{P - P^-}{P^+ - P^-}; L_2 = \frac{P^+ - P}{P^+ - P^-}$, the member functions of Q are $M_1 = \frac{Q - Q^-}{Q^+ - Q^-}; M_2 = \frac{Q^+ - Q}{Q^+ - Q^-}$, and the member functions of X_e are $N_1 = \frac{X_e - X_e^-}{X_e^+ - X_e^-}; N_2 = \frac{X_e^+ - X_e}{X_e^+ - X_e^-}$.

Suppose

$h_1 = L_1 M_1 N_1; h_2 = L_1 M_1 N_2; h_3 = L_1 M_2 N_1; h_4 = L_1 M_2 N_2$

and

$h_5 = L_2 M_1 N_1; h_6 = L_2 M_1 N_2; h_7 = L_2 M_2 N_1; h_8 = L_2 M_2 N_2$

. If we define

$$\alpha_i = \frac{h_i}{\sum_{j=1}^{8} h_j}; i = 1,2,...,8$$

After we applied the fuzzification according rule 1-8, then we applied defuzzification such as below

$$\dot{x} = \sum_{i=1}^{8} \alpha_i (A_i x_i + Bu) \quad (8)$$

And the output of system is

$$y = Cx_i \tag{9}$$

III. Design Controller Fuzzy Model of SMIB

There are some design controller methods such as state feedback controller $u = -Fx$, and output feedback controller $u = Fy$, where y is output such as equation (9). In this paper we design the controller by using the output feedback controller. The output feedback fuzzy controller is constructed by PDC is

$$u(t) = Fy \qquad u(t) = FCx_i \tag{10}$$

We substitute equation (10) into equation (8), we obtain

$$\dot{x} = \sum_{i=1}^{8} \alpha_i (A_i x_i + BF_i C x_i)$$

Or we can write as

$$\dot{x} = \sum_{i=1}^{8} \alpha_i (A_i + BF_i C) x_i \tag{11}$$

The problem of design controller is determining the matrix F_i such that the system in equation (11) is stable. One of methods to analyze the stability of system is by determining the eigen value of $\alpha_i(A_i + BF_i C)$ and the other is by defining the Lyapunov function. In this paper, we analyze the eigen value of matrix $\alpha_i(A_i + BF_i C)$. The system is stable if the real part of eigen value is negative or lay on the left half plane of complex space.

The eigen value of matrix $\alpha_i(A_i + BF_i C)$ is obtained by solving Equation (12)

$$\left|\lambda I - \alpha_i(A_i + BF_i C)\right| = 0 \tag{12}$$

$$\begin{bmatrix} \lambda & \alpha_i \omega_0 & 0 & 0 \\ -\frac{\alpha_i T_m}{M\delta} & \lambda & \alpha_i S_{1i} & 0 \\ 0 & 0 & \lambda + \alpha_i S_{2i} & -\frac{\alpha_i}{T'_{d0}} \\ -\frac{\alpha_i K_E}{T_E} f_{i1} & -\frac{\alpha_i K_E}{T_E} f_{i2} & -\alpha_i S_{3i} & \lambda + \frac{\alpha_i}{T_E} \end{bmatrix} = 0$$

The polynomial of eigen value is

$$\lambda^4 + \left(\frac{1}{T_E} + S_{2i}\right)\alpha_i \lambda^3 + \left(\frac{S_{2i}}{T_E} - \frac{S_{3i}}{T'_{d0}} - \frac{\omega_0 T_m}{M\delta}\right)\alpha_i^2 \lambda^2 + \alpha_i^3 \left(S_{1i}\frac{1}{T'_{d0}}\frac{K_E}{T_E} f_{i2} - \omega_0 \frac{T_m}{M\delta}\left(\frac{1}{T_E} + S_{2i}\right)\right)\lambda - \alpha_i^4 \omega_0 \frac{T_m}{M\delta}\left[\frac{S_{2i}}{T_E} - \frac{S_{3i}}{T'_{d0}}\right] - \frac{S_{1i}\omega_0 \alpha_i^3 K_E}{T_E} f_{i1} \frac{1}{T'_{d0}} = 0$$

Furthermore, we made The Routh Hurwitz [5] table as follows

$$\begin{vmatrix} 1 & a_2 & a_4 & 0 \\ a_1 & a_3 & 0 & 0 \\ b_1 & a_4 & 0 & 0 \\ c_1 & 0 & & \\ a_4 & 0 & & \end{vmatrix}$$

Where

$$a_0 = 1; a_1 = \left(\frac{1}{T_E} + S_{2i}\right)\alpha$$

$$a_2 = \left(\frac{S_{2i}}{T_E} - \frac{S_{3i}}{T'_{d0}} - \frac{\omega_0 T_m}{M\delta}\right)\alpha_i^2$$

$$a_3 = \alpha_i^3 \left(S_{1i}\frac{1}{T'_{d0}}\frac{K_E}{T_E} f_{i2} - \omega_0 \frac{T_m}{M\delta}\left(\frac{1}{T_E} + S_{2i}\right)\right)$$

$$a_4 = -\alpha_i^4 \omega_0 \frac{T_m}{M\delta}\left[\frac{S_{2i}}{T_E} - \frac{S_{3i}}{T'_{d0}}\right] - \frac{S_{1i}\omega_0 \alpha_i^3 K_E}{T_E} f_{i1} \frac{1}{T'_{d0}}$$

According the Routh-Hurwitz if , system (6) is stable if

$$a_1 > 0;\ b_1 = \frac{a_1 a_2 - a_3}{a_1} > 0;\ b_2 = a_4$$
$$c_1 = \frac{b_1 a_3 - a_1 b_2}{b_1} > 0;\ c_2 = 0 \tag{13}$$
$$d_2 = \frac{c_1 b_2 - 0}{c_1} = a_4 > 0$$

By calculating and arranging Equation (13) then we get this system is stable if the output feedback gain $F_i = [f_{i1} \quad f_{i2}]$ satisfy

$$f_{i2} > \omega_0 \frac{T_m}{M\delta}(1 + S_{2i}T_E)\frac{T'_{d0}}{S_{1i}K_E}$$
$$f_{i1} < \frac{T_m}{S_{1i}K_E M\delta}\left[-T'_{d0}S_{2i} + T_E S_{3i}\right] \tag{14}$$

The output feedback gain will be substituted to Equation (10) to obtain the input controller and the performance of PSS will be obtained by substituting Equation (14) to Equation (11)

IV. SIMULATION AND RESULT

Suppose, there are two states which can measured such as δ and ω . The output feedback gain $F_i = [f_{i1} \quad f_{i2}]$ will be chosen such that Equation (14) is satisfied. Suppose

$f_1^* = \frac{T_m}{S_{1i}K_E M\delta}\left[-T'_{d0}S_{2i} + T_E S_{3i}\right]$ and

$f_2^* = \omega_0 \frac{T_m}{M\delta}(1 + S_{2i}T_E)\frac{T'_{d0}}{S_{1i}K_E}$ then we choose

$F_i = [f_{i1} \quad f_{i2}]$ such that $f_{i1} < f_1^*$ and $f_{i2} > f_2^*$.

In this simulation we take the initial condition

$$\delta_0 = 0.2; \omega_0 = 377; E_{q0} = 0.2; E_{fd0} = 0.1$$

The parameters are [3]

$x_q = 1.7;\ x_d = 1.8;\ x_d' = 0.3;\ T_d' = 8;\ M = 13$

$V_\infty = 1.0;\ KE = 200;\ TE = 0.001;\ T_{d0} = 8;\ x_{de} = 0.1$

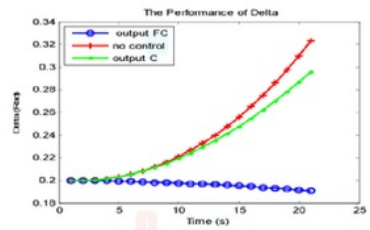

Figure 3. The Performance of δ

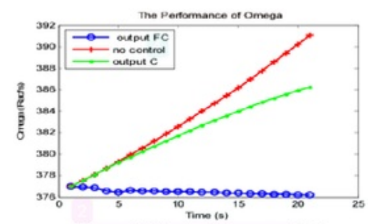

Figure 4. The Performance of ω

Figure 3 and figure 4 state the performance of δ, ω respectively. The performance of δ, ω are divergence for SIMB system without control and SIMB system with control without fuzzy. But the performance of δ, ω for SIMB system with fuzzy control are converge. So, it is important to design fuzzy control for this SIMB.

At first time we choose output feedback gain $f_{i1} = 0.8 f_1^*$ and $f_{i2} = 1.2 f_2^*$ for system with output feedback fuzzy control. The performance of δ, ω, P_e, Q are state in figure 5. The magnitudes of δ, ω are decrease, and the magnitudes of P_e, Q are converge.

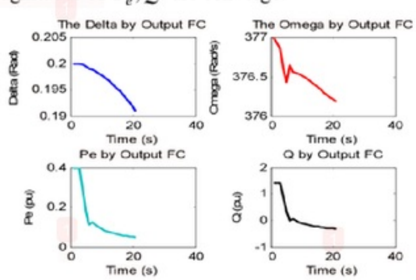

Figure 5. $f_{1i} = 0.8 f_1^*; f_{2i} = 1.2 f_2^*$

It must be chosen the value of f_{1i}, f_{2i} such that the performance of SIMB system is good. In this simulation we choose some value of f_{1i}, f_{2i}. The simulation results are stated in Figure 6 – 10

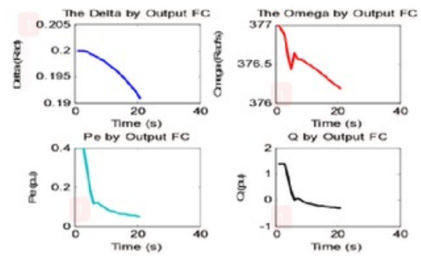

Figure 6. $f_{1i} = -1 f_1^*, f_{2i} = 1.2 f_2^*$

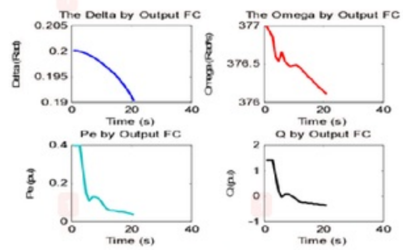

Figure 7. $f_{1i} = -4 f_1^*, f_{2i} = 4 f_2^*$

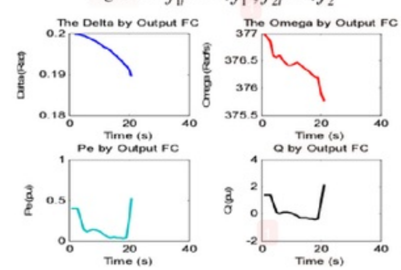

Figure 8. $f_{1i} = -5 f_1^*; f_{2i} = 5 f_2^*$

From figure 5-8 , we know that the value of $f_{1i}; f_{2i}$ can be chosen until $f_{1i} = -4 f_1^*; f_{2i} = 4 f_2^*$ and still give good performance, but for $f_{1i} = -5 f_1^*; f_{2i} = 5 f_2^*$ give bad performance for P_e, Q.

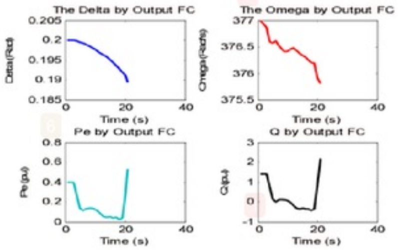

Figure 9. $f_{1i} = 0.8 f_1^*, f_{2i} = 5 f_2^*$

Figure 9 is the performance of SIMB with output feedback fuzzy controller for $f_{1i} = 0.8 f_1^*, f_{2i} = 5 f_2^*$. We choose $f_{1i} < f_1^*; f_{2i} > f_2^*$, but f_{2i} is too large, so the performance of P_e, Q also divergence such as case $f_{1i} = -5 f_1^*, f_{2i} = 5 f_2^*$ in figure 8.

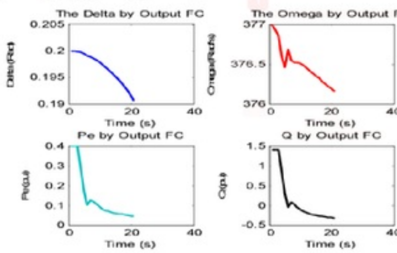

Figure 10. $f_{1i} = -5 f_1^*; f_{2i} = 2 f_2^*$

From figure 10, we see that the performance of SIMB is still good when we take $f_{1i} = -5 f_1^*; f_{2i} = 2 f_2^*$. From figure 5-10 we conclude that we can choose the output feedback gain $F_i = [f_{1i} \quad f_{2i}]$ such that

$-5 f_1^* \le f_{1i} \le 0.8 f_1^*$; and $1.2 f_2^* \le f_{2i} < 5 f_2^*$

The next simulation we take $f_{1i} > f_1^*; f_{2i} < f_2^*$ and the simulation result are given in figure 11-13.

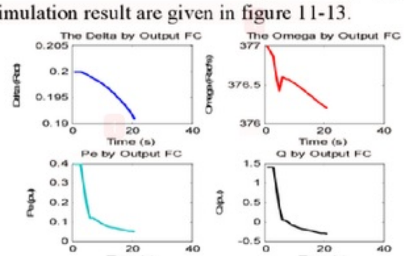

Figure 11. $f_{1i} = 5 f_1^*; f_{2i} = 0.8 f_2^*$

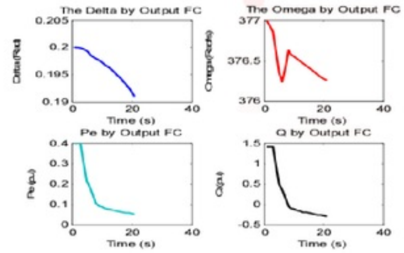

Figure 12. $f_{1i} = 5 f_1^*; f_{2i} = -f_2^*$

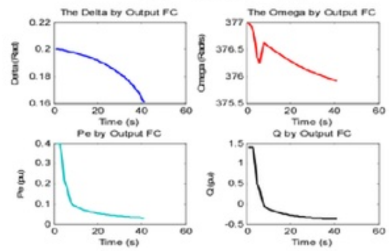

Figure 13. $f_{1i} = 120 f_1^*; f_{2i} = -f_2^*$

From figure 11-13, we see that we can choose the output feedback gain $F_i = [f_{1i} \quad f_{2i}]$ such that $f_{1i} \le 120 f_1^*$; and $f_2^* \ge -f_{2i}$.

So, the interval of output feedback gain which give good performance is $F_i = [f_{1i} \quad f_{2i}]$ such that $-5 f_1^* \le f_{1i} \le 120 f_1^*$; and $-f_2^* \le f_{2i} < 5 f_2^*$

We also did simulation with difference initial condition such as $\delta_0 = 0.9; \omega_0 = 200$, the performance SMIB represent on figure 14-16 as below

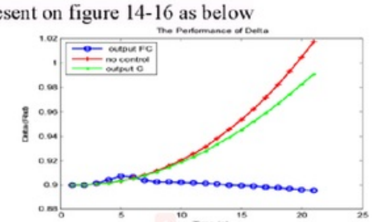

Figure 14. The performance of δ

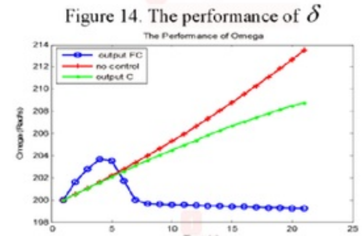

Figure 15. The Performance of ω

From figure 14 -15, we see that the performance of SIMB without control and with output control without fuzzy are divergence, but the performance of SIMB with output fuzzy control is converge. Some simulation result with difference value of output feedback gain are represented in figure 16 -17.

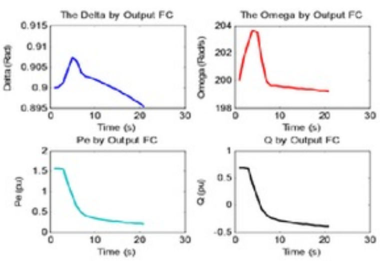

Figure 16. $f_{1i} = 0.8 f_1^*; f_{2i} = 1.2 f_2^*;$
$\delta_0 = 0.9; \omega_0 = 200$

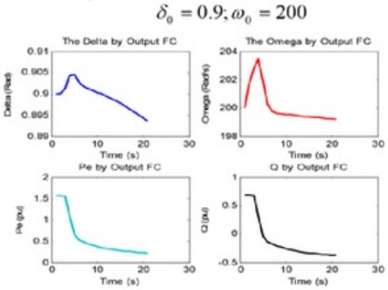

Figure 17. $f_{1i} = 5 f_1^*; f_{2i} = -f_2^*;$
$\delta_0 = 0.9; \omega_0 = 200$

Figure 16 -17 state that the performance of SIMB output feedback fuzzy control are good for other initial condition.
From those simulations, we know that the design controller by using the fuzzy output feedback controller give the stable performance of δ, ω. The performances are depend on value of output feedback gain but not depend on initial condition of δ_0, ω_0.

V. CONCLUTION

In this paper we discuss about the designing controller based of fuzzy output feedback controller. The output feedback gain is determined by using Ruth Hurwitz criteria. From the analyze and simulation we conclude that

- The output feedback controller (without fuzzy) can't be applied as design controller
- The fuzzy output feedback can be used to design controller of SMIB
- The fuzzy output feedback is independent from the initial condition, but dependent on the value of output feedback gain
- The value of output feedback gain are available for certain interval.

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