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# Fuzzy Logic Based on Lyapunov Solution in Power System Stability Improvement

Tamaji and Imam Robandi
Department of Electrical Engineering, Sepuluh Nopember Institute of Technology,
Surabaya, Indonesia

**Abstract:** There are many methods to design controller of power system. In this study, we design the controller of generator power system to stabilize the electricity supply. The system is assumed the single machine infinite bus. The mathematical model of power system stabilizer is non-linear. The first time, the system is written in the state space system, then it is designed the output feedback controller by using Lyapunov and fuzzy Lyapunov method, finally the performance of SMIB by Lyapunov and fuzzy Lyapunov method are compared with the performance by using pole placement and routh-hurwitz method. The simulation has been done with some parameters feedback gain such as the feedback gain K, $K_{fuzzy}$, $K_{pole}$, $K_{RH}$ based on Lyapunov, fuzzy Lyapunov, fuzzy pole placement and fuzzy Routh-Hurwitz method, respectively. Based on our simulation we know that Lyapunov and fuzzy Lyapunov have almost same performance and have the best performance compared with fuzzy pole placement and fuzzy Routh-Hurwitz.

**Key words:** Single machine infinite bus, output feedback controller, Lyapunov, fuzzy Lyapunov function, fuzzy pole placement, fuzzy Routh-Hurwitz

## INTRODUCTION

There are some methods to design the controller of system such as state feedback controller, output feedback controller, sliding mode control-SMC and others. Here, we design the controller of generator power systems. The stability of generator power system is necessary to keep the stability of electricity supply. The mathematical model of Power System Stabilizer-PSS is Single Machine Infinite Bus (SMIB). This mathematical model is a non linear system. There are many methods to design the controller of PSS such as improved swarm optimization to stabilize the SMIB (Alfi and Khosravi, 2012), the robust control PSS based on pole placement and Linear Matrix Inequality-LMI (Ataei *et al*., 2012; Challoshtori, 2012), direct feedback linearization is applied to design the controller for SMIB (Yadaiah and Romana, 2007). Some researchers applied the design control methods in linear system. Here, it is designed the controller for non-linear system.

The non linear system of SMIB is unstable so, it is necessary to design the controller. In this study, the output feedback controller of SMIB is design by constructing the Lyapunov function. The Lyapunov function is a part of LMI method. Some researchers have been used LMI to design the controller of SMIB such as Mondal (2012): the Linear Matrix Inequality (LMI) has been applied to design an internally stabilizing controller for the TCSC that satisfy $H_\infty$ norm constraint. Fuzzy logic controller is applied to enhance the stability of SMIB (Sedaghati *et al*., 2014; Jasmitha and Vijayasanthi, 2015) and power system stability is enhanced through a novel stabilizer developed around an adaptive fuzzy sliding mode approach which applies the Nussbaum gain to a non-linear model of a Single-Machine Infinite-Bus (SMIB) (Nechad *et al*., 2013). Actually, in LMI method, we also construct the Lyapunov function V(x, t) as energy of system is positive and the velocity $dV(x, t)/dt<0$. They used the LMI toolbox and applied in linear system. In this study, it is constructed the Lyapunov function by analytical method and retained the SMIB system as non linear system. The SMIB system is written as state space system and the feedback gain is determined based on Lyapunov method. In this study, it is also applied the fuzzy Lyapunov method. The fuzzification is applied in the state space system, the output feedback gain is determined by Lyapunov and finally it is applied defuzzification to get stabilize SMIB system.

The performance of SMIB system by Lyapunov and Fuzzy Lyapunov method are compared with the other methods of design controller such as fuzzy pole placement and fuzzy Routh-Hurwitz.

**SMIB performancy:** Single machine infinite bus of the generator power system can be modeled as non-linear model (Yadaiah and Romana, 2007).

**Corresponding Author:** Tamaji, Department of Electrical Engineering, Sepuluh Nopember Institute of Technology, Surabaya, Indonesia

$$\dot{\delta} = \omega_0 \omega \quad (1)$$

$$\dot{\omega} = (T_m - E_q^{'} I_q - (x_q - x_d^{'}) I_d I_q)/M \quad (2)$$

$$\dot{E}_q^{'} = (-E_q^{'} - (x_q - x_d^{'}) I_d + E_{fd}^{'})/T_{d0}^{'} \quad (3)$$

$$\dot{E}_{fd}^{'} = \frac{K_E}{T_E}(V_{ref} - V_T + u_{pss}) - \frac{1}{T_E} E_{fd}^{'} \quad (4)$$

Where:

$$V_T = \sqrt{V_d^2 + V_q^2}$$
$$V_d = -X_e I_q + V_s \sin\delta$$
$$V_q = X_e I_q + V_s \cos\delta$$
$$P = \frac{E_q^{'} V_s}{x_{d\varepsilon}^{'}} \text{Sin}\delta$$
$$Q = \frac{E_q^{'} V_s}{x_{d\varepsilon}^{'}} \text{Cos}\delta - \frac{V_s^2}{x_{d\alpha}^{'}}$$

The state variable $\delta$, $\omega$, $E_q^{'}$ $E_{fd}^{'}$ is angle, angular velocity, induced EMF proportional to field current and generator field voltages, respectively. The non-linear system of SMIB (Eq. 1-4) is unstable and the performance of system is presented on Fig. 1. It is necessary to design the controller to obtain the stable system. In this study, it is design the controller by constructing the Lyapunov function and fuzzy Lyapunov function. The first time, it is proposed the state space system as below:

$$\begin{bmatrix} \dot{\delta} \\ \dot{\omega} \\ \dot{E}_q^{'} \\ \dot{E}_{fd}^{'} \end{bmatrix} = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ 0 & a & -b & 0 \\ 0 & 0 & -c & \frac{1}{T_0^{'}} \\ 0 & 0 & d & -\frac{1}{T_E} \end{bmatrix} \begin{bmatrix} \delta \\ \omega \\ E_q^{'} \\ E_{fd}^{'} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{K_E}{T_E} \end{bmatrix} u_{pss} \quad (5)$$

Where:

$$a = \frac{\left(T_m - (x_q - x_d^{'}) I_d I_q\right)}{M\omega}$$
$$b = \left[\left(\frac{Px'_{d\varepsilon}}{E_q^{'} X_e M} - \frac{V_d}{X_e M}\right)\right]$$
$$c = \left(\frac{1}{T_{d0}^{'}} + \frac{(x_d - x_d^{'}) I_d}{T_{d0}^{'} E_q^{'}}\right)$$
$$d = \frac{K_E}{T_E E_q^{'}}(V_{ref} - V_T)$$

The state space system in Eq. 5 can be written as general model of system as follows:

$$\dot{X} = AX + Bu \quad (6)$$

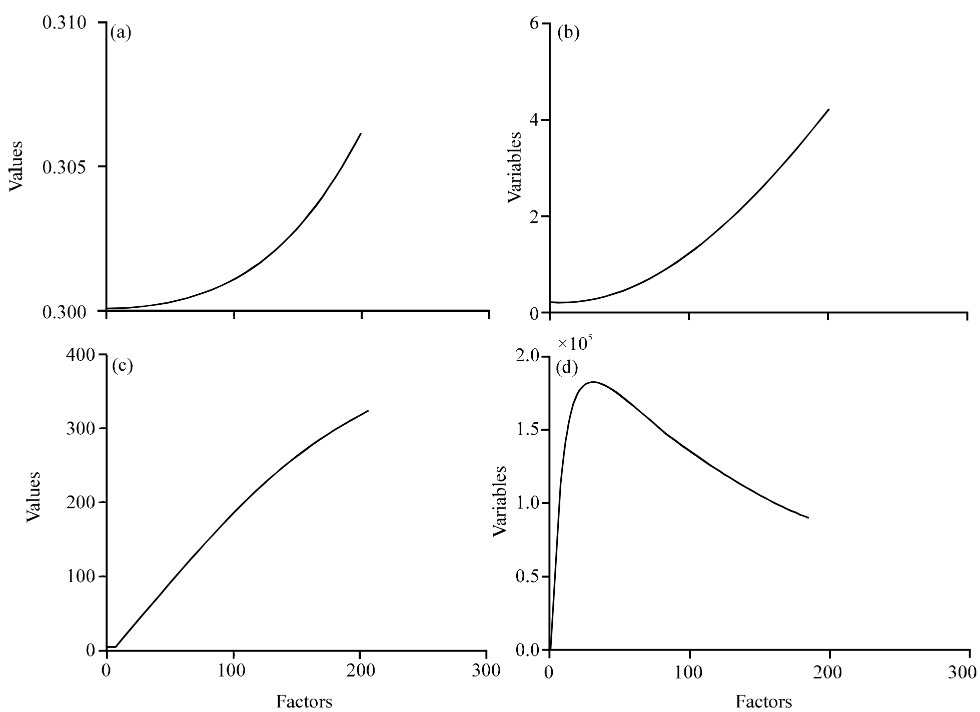


Fig. 1: SMIB performance without control: a) Delta; b) Omega; c) $E_q$ and d) $E_{fd}$

With output Eq. 7:

$$y = CX \quad (7)$$

Where:

$$X = \begin{bmatrix} \delta & \omega & E_q^{'} & E_{fd}^{'} \end{bmatrix}^T$$

$$A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ 0 & a & -b & 0 \\ 0 & 0 & -c & \frac{1}{T_0^{'}} \\ 0 & 0 & d & -\frac{1}{T_E} \end{bmatrix} B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{K_E}{T_E} \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & 1 & 0 & 0 \end{bmatrix}$$

## MATERIALS AND METHODS

**Fuzzy logic based on Lyapunov:** In this research, it is designed the output feedback controller. In output feedback controller, it is determined the output feedback gain K in control, u = -Ky such that system:

$$\dot{X} = AX - BKy$$

Or:

$$\dot{X} = (A - BKC)X \quad (8)$$

is stable. There are some methods to determine the feedback gain K in feedback controller problem such as pole placement, Ruth-Hurwitz method, fuzzy control and lmi methods. Here, it is used the lmi method or Lyapunov method.

**The Lyapunov output feedback controller:** Control system design by LMI method, actually, it is constructed the Lyapunov function V(x, t) such that:

$$V(x,t) \geq 0; V(0,0) = 0$$

$$\frac{dV}{dt}(x,t) < 0$$

It is chosen the Lyapunov function V(x, t) = $x^T{}_{Rx}$ where, R is symmetry definite positive matrix:

$$\frac{dV}{dt} = \dot{V}(x,t) = \dot{x}^T Rx + x^T R\dot{x} \quad (9)$$

Substitute Eq. 8 into Eq. 9, it is obtained:

$$\dot{V}(x,t) = x^T\left((A - BKC)^T R + R(A - BKC)\right)x \quad (10)$$

Equation 8 is stable if $\dot{V}(x,t) < 0$. So, the problem of control design by Lyapunov method is, how determine the output feedback gain K and matrix symmetry R in Eq. 10 such that matrix $(A\text{-}BKC)^T$ R+R (A-BKC) definite negative. Suppose R semi definite positive matrix:

$$R = \begin{bmatrix} r_{11} & 0 & 0 & 0 \\ 0 & r_{22} & 0 & 0 \\ 0 & 0 & r_{33} & 0 \\ 0 & 0 & 0 & r_{44} \end{bmatrix}$$

where, $r_{ii}>0$, i = 1, 2, 3, 4. Then:

$$\left(R(A - BKC)\right)^T + R(A - BKC) =$$

$$\begin{bmatrix} 0 & r_{11}\omega_0 & 0 & 0 \\ r_{11}\omega_0 & 2r_{22}a & -r_{22}b & \frac{K_E}{T_E}Kr_{44} \\ 0 & -r_{22}b & -2r_{33}c & r_{44}d + \frac{1}{T_0^{'}}r_{33} \\ 0 & \frac{K_E}{T_E}Kr_{44} & r_{44}d + \frac{1}{T_0^{'}}r_{33} & -2r_{44}\frac{1}{T_E} \end{bmatrix}$$

Then:

$$\frac{dV}{dt} = 2r_{11}\omega_0\omega\delta + 2r_{22}a\omega^2 - 2r_{22}bE_q\omega + 2\frac{K_E}{T_E}Kr_{44}E_{fd}\omega -$$

$$2r_{33}cE^2{}_q + 2r_{44}dE_{fd}E_q + \frac{2}{T_0^{'}}r_{33}E_{fd}E_q + -2r_{44}\frac{1}{T_E}E^2{}_{fd}$$

So, the SMIB system will be stable if:

$$2r_{11}\omega_0\omega\delta + 2r_{22}a\omega^2 - 2r_{22}bE_q\omega + 2\frac{K_E}{T_E}Kr_{44}E_{fd}\omega -$$

$$2r_{33}cE^2{}_q + 2r_{44}dE_{fd}E_q + \frac{2}{T_0^{'}}r_{33}E_{fd}E_q - 2r_{44}\frac{1}{T_E}E^2{}_{fd} < 0$$

Or:

$$\begin{bmatrix} r_{11} \\ r_{22} \\ r_{33} \\ r_{44} \end{bmatrix}^T \text{diag}\begin{pmatrix} \omega_0\omega, a\omega - bE_q, \frac{1}{T_0^{'}}E_{fd} - cE_q, \\ \frac{K_E}{T_E}K\omega + dE_q - \frac{1}{T_E}E_{fd} \end{pmatrix}\begin{bmatrix} \delta \\ \omega \\ E_q \\ E_{fd} \end{bmatrix} < 0$$

Because $r_{11}$, $r_{22}$, $r_{33}$, $r_{44}$ positive and variables δ, ω, $E_q$, $E_{fd}$ also positive then:

$$\left(a\omega - bE_q\right) < 0; \left(\frac{1}{T_0^{'}}E_{fd} - cE_q\right) < 0$$

$$\left(\frac{K_E}{T_E}K\omega + dE_q - \frac{1}{T_E}E_{fd}\right) < 0$$

So:

$$\left(\frac{K_E}{T_E}K\omega + dE_q - \frac{1}{T_E}E_{fd}\right) < 0 \rightarrow K < \left(\frac{1}{T_E}E_{fd} - dE_q\right)\frac{T_E}{\omega K_E}$$

and $r_{44}$ larger than $r_{11}$, $r_{22}$, $r_{33}$. The output feedback gain of SMIB by using Lyapunov function is:

$$K < \left( \frac{1}{T_E} E_{fd} - dE_q \right) \frac{T_E}{\omega K_E}$$

The output feedback gain is depend on variables ω, $E_q$ and $E_{fd}$. It can be chosen:

$$K = \beta \left( \frac{1}{T_E} E_{fd} - dE_q \right) \frac{T_E}{\omega K_E}; 0 < \beta < 1 \qquad (11)$$

As output feedback gain and substituted Eq. 11-8 so that system SMIB stable. Here is also applied the fuzzy controller to design the controller of SMIB and we call Fuzzy Lyapunov output feedback controller.

**Fuzzy Lyapunov output feedback controller:** In this research, it applied the fuzzy controller to avoid the non linearity of SMIB system. It is chosen the fuzzy parameters, P, Q, $X_e$. The interval of parameters are $P \in [P^- \; P^+]$; $Q \in [Q^- \; Q^+]$ and $X_e \in [X_e^- \; X_e^+]$. Suppose $P \in [0.4 \; 1]$; $Q \in [-0.2 \; 0.5]$ and $X_e \in [0.2 \; 0.4]$ then the members function of P, Q, $X_e$ can be described in Fig. 2. There are three parameters, so that there are 8 rules of SMIB system (Tanaka and Wang, 2001).

**Rule 1:**

$\text{If...(t)is...}P^- \text{ and...Q(t)is...}Q^- \text{ and...}X_e(t)\text{is...}X_e^-$

Then

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

$y(t) = Cx(t)$

**Rule 2:**

$\text{If...P(t)is...}P^- \text{ and...Q(t)is...}Q^- \text{ and...}X_e(t)\text{is...}X_e^+$

Then

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

$y(t) = Cx(t)$

...

...

...

**Rule 8:**

$\text{If...P(t)is...}P^+ \text{ and...Q(t)is...}Q^+ \text{ and...}X_e(t)\text{is...}X_e^+$

Then

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

$y(t) = Cx(t)$

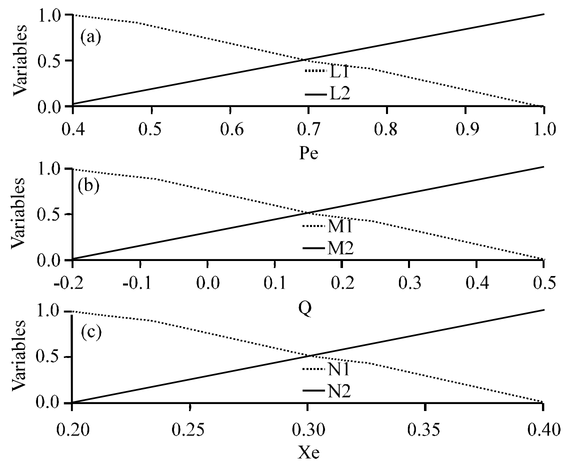


Fig. 2: Members function of Pe, Q, $X_e$

The Lyapunov output feedback controller is applied for each rule and obtained the Lyapunov output feedback gain $K_i$, i = 1, 2, 3, ..., 8. From Eq. 11, the feedback gain is:

$$K_i < \left( \frac{1}{T_E} E_{fd}^i - dE_q^i \right) \frac{T_E}{\omega^i K_E}; i = 1, 2, 3, \ldots, 8$$

and such as in Lyapunov output feedback controller, it can be chosen:

$$K_i = \beta \left( \frac{1}{T_E} E_{fd}^i - dE_q^i \right) \frac{T_E}{\omega^i K_E} \qquad (12)$$

for i = 1, 2, 3,..., 8 and 0<β<1. By substituting the feedback gain $K_i$ Eq. 12 in to SMIB system Eq. 8, it is obtained the eight of systems. Suppose, the member functions of P, Q and $X_e$ as follows:

$$L_1 = \frac{P - P^-}{P^+ - P^-}; L_2 = \frac{P^+ - P}{P^+ - P^-}$$

$$M_1 = \frac{Q - Q^-}{Q^+ - Q^-}; M_2 = \frac{Q^+ - Q}{Q^+ - Q^-}$$

$$N_1 = \frac{X_e - X_e^-}{X_e^+ - X_e^-}; N_2 = \frac{X_e^+ - X_e}{X_e^+ - X_e^-}$$

And:

$$h_1 = L_1 M_1 N_1; h_2 = L_1 M_1 N_2; h_5 = L_2 M_1 N_1; h_6 = L_2 M_1 N_2;$$
$$h_3 = L_1 M_2 N_1; h_4 = L_1 M_2 N_2; h_7 = L_2 M_2 N_1; h_8 = L_2 M_2 N_2$$

Then, the state space Eq. 8 can be written as a fuzzy model:

$$\dot{x} = \sum_{i=1}^{8} h_i \left( A_i - BK_i C \right) x_i \qquad (13)$$

Some simulation of the SMIB's performance are made based on Eq. 12 and 13.

## RESULTS AND DISCUSSION

In this simulation we take some parameters from (Yadaiah and Romana, 2007), $\omega_0 = 0.2$; $T_m = 8$; $x'_q = 1.2$; $x_d = 1.8$; $M = 13$; $K_E = 20$; $T_E = 0.001$; $T'_{d0} = 8$ with initial conditions $\delta = 0.3$; $\omega = 0.2$; $E_q = 0.2$ and $E_{fd} = 0.1$. It has been done also the others output feedback design controller such as pole placement, routh-hurwitz, fuzzy pole placement and fuzzy Routh-Hurwitz methods in (Tamaji and Robandi, 2017). From references (Tamaji and Robandi, 2017) the output feedback gain by pole placement:

$$K_{pole} = \left(\lambda_1\lambda_2\lambda_3 + a\frac{d}{T'_0} - ac\frac{1}{T'_E}\right)\frac{T'_0 T_E}{bK_E}$$

Where:

$$\lambda_2 = -\alpha\left(c + \frac{1}{T_E} - a\right) 0 < \alpha < 1$$

$$\lambda_1 = -\frac{1}{2}\left(c + \frac{1}{T_E} - a + \lambda_2\right) \pm \frac{1}{2}\sqrt{\left(c + \frac{1}{T_E} - a + \lambda_2\right)^2 - 4\left(\lambda_2^2 + \left(c + \frac{1}{T_E} - a\right)\lambda_2 + \left(\frac{c}{T'_E} - \frac{d}{T'_0} - ca - \frac{a}{T_E}\right)\right)}$$

$$\lambda_3 = -\left(c + \frac{1}{T_E} - a + \lambda_1 + \lambda_2\right)$$

The output feedback gain of Routh-Hurwitz:

$$K_{RH} = \beta\left(a\frac{d}{T'_0} - ac\frac{1}{T'_E}\right)\frac{T_E T'_0}{bK_E}; 0 < \beta < 1$$

Based on those feedback gains, it has been done some simulation to get the performance of SMIB with output feedback controller. The first simulation is taken P∈[-0.2 2.2]: Q∈[-0.4 1.8] and $X_e$∈[-0.4 2.2] and $\alpha = 0.002$; $\beta = 0.01$. For this parameters is taken two cases of P, Q, $X_e$ as constant, p = 1.8; Q = 1.2; $X_e$ = 1.8 (Fig. 3-10) and as function p = 0.8 sin (t); Q = 0.2 sin (t); $X_e$ = 0.8 sin (t) (Fig. 10-18).

Figure 3-6 show the performance of design controller of SMIB by using fuzzy pole placement, fuzzy Routh-Hurwitz, LMI and fuzzy LMI. From those figures seem that LMI or Lyapunov function, fuzzy Routh-Hurwitz and the fuzzy LMI output feedback controller give the stable performances. But the fuzzy pole placement give a bad performance of SMIB, the variable $\delta$ and $\omega$ divergence and there is the overshoot event on $E_q$ and $E_{fd}$.

Figure 7-10, show the LMI and fuzzy LMI output feedback controller for SMIB. The performance of fuzzy

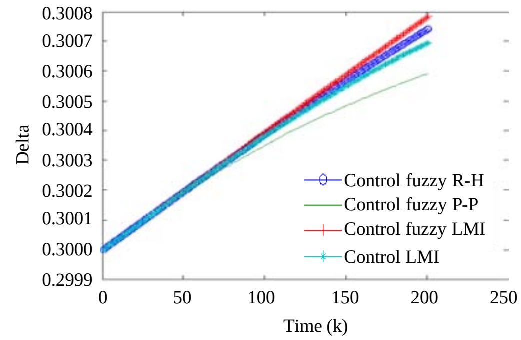


Fig. 3: Performance of $\delta$ ($\alpha = 0.002$; $\beta = 0.01$)

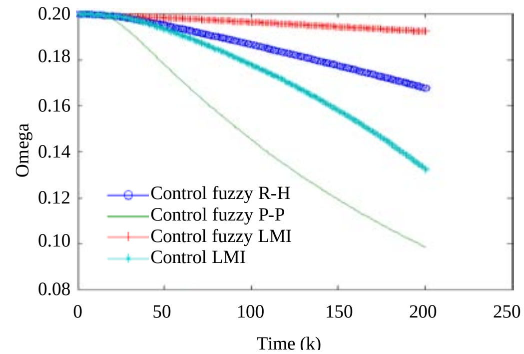


Fig. 4: The performance of $\omega$ ($\alpha = 0.002$; $\beta = 0.01$)

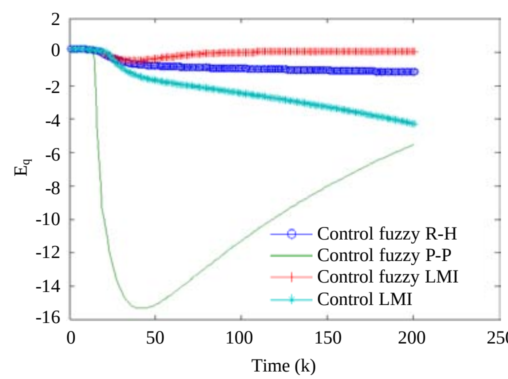


Fig. 5: The performance of $E_q$ ($\alpha = 0.002$; $\beta = 0.01$)

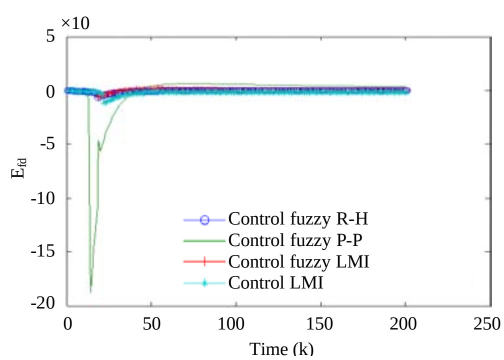


Fig. 6: The performance of $E_{fd}$ ($\alpha = 0.002$; $\beta = 0.01$)

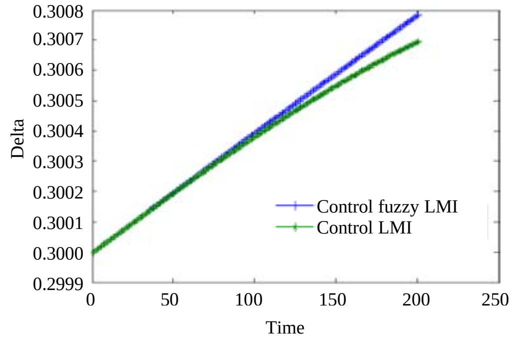


Fig. 7: The performance of $\delta$ ($\beta = 0.01$)

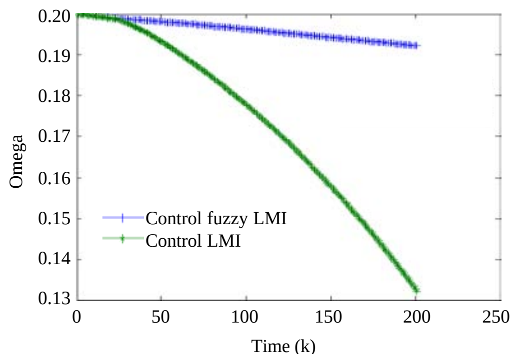


Fig. 8: The performance of $\omega$ ($\beta = 0.01$)

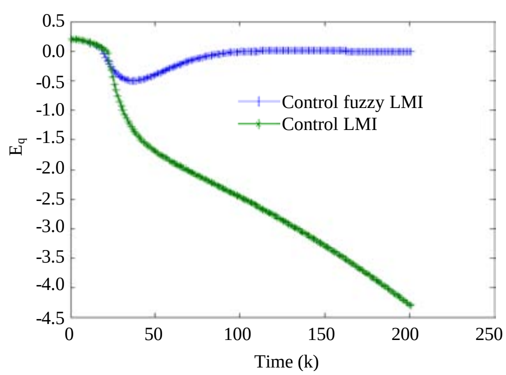


Fig. 9: The performance of $E_q$ ($\beta = 0.01$)

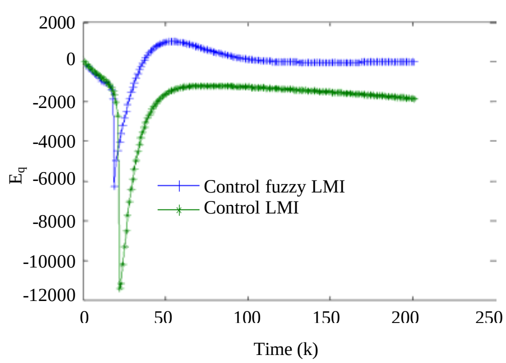


Fig. 10: The performance of $E_{fd}$ ($\beta = 0.01$)

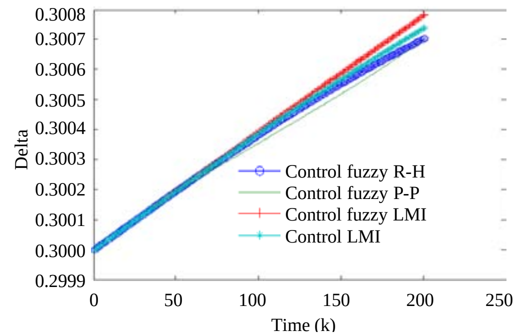


Fig. 11: The performance of $\delta$ ($\alpha = 0.002$; $\beta = 0.01$)

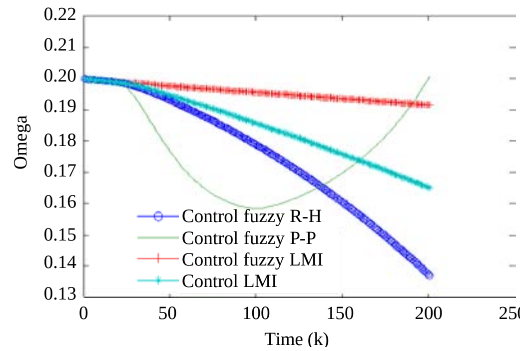


Fig. 12: The performance of $\omega$ ($\alpha = 0.002$; $\beta = 0.01$)

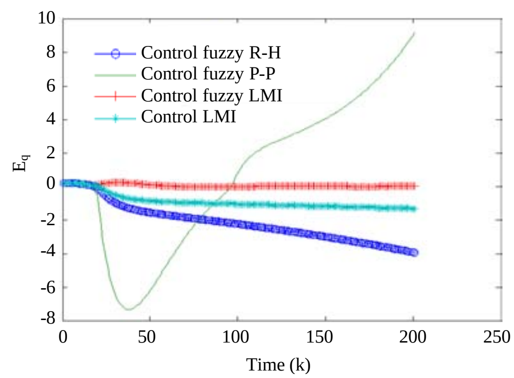


Fig. 13: The performance $E_q$ ($\alpha = 0.002$; $\beta = 0.01$)

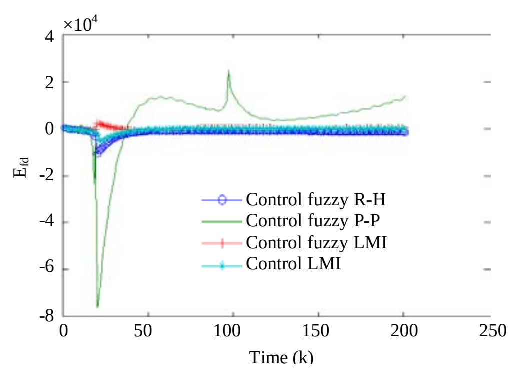


Fig. 14: The performance of $E_{fd}$ ($\alpha = 0.002$; $\beta = 0.01$)

LMI (Lyapunov) output feedback controller give better result than LMI (Lyapunov) output feedback controller for constant P, Q, $X_e$.

The second simulation, it is applied those methods for the same parameters with dynamical of P; Q; $X_e$. Suppose, P = 0.8 sin (t); Q = 0.2 sin (t); $X_e$ = 0.8 sin (t). The simulation results are presented as Fig. 11-14.

For P, Q, $X_e$ as dynamical functions the performance of SMIB by using Fuzzy Pole Placement are worst, specially the performance of $E_q$ and $E_{fd}$. The performance of δ are almost the same as for all methods. The performance of ω, $E_q$, $E_{fd}$ by using Fuzzy LMI (Lyapunov) has best result than others. The performance of SMIB by using LMI and Fuzzy LMI are presented on Fig. 15-18. The value of angular velocity ω tends to 0.2.

The performance of δ is almost the same between by using the LMI output feedback controller with the Fuzzy output feedback controller (Fig. 15). The performance of ω, $E_q$ by using Fuzzy LMI is more stable than by using LMI (Fig. 16-17). Figure 18 shows that there are the overshooting on the performance of $E_{fd}$. The overshooting of $E_{fd}$ by using LMI is larger than by using Fuzzy LMI.

In order to define the difference between LMI output feedback controller with LMI Fuzzy output feedback controller, it has been done the other simulation with different value of β. It taken β = 0.1 and β = 0.5. The performance of δ, ω are almost the same with simulation before (β = 0.01) but the performance of $E_q$ and $E_{fd}$ are different with the simulation with β = 0.01. The results of simulation are presented on Fig. 19-22 for β = 0.1 and Fig. 19-26 for β = 0.5. For β = 0.1, the performance $E_q$ by using Fuzzy LMI is more stable than by using LMI but the performance of $E_{fd}$ has larger overshoot than by using LMI.

For β = 0.5 and P, Q, $X_e$ as constant the performance $E_q$ by using Fuzzy LMI has overshoot and then converge to 0.4. The overshooting of $E_q$ larger than the value of $E_q$ by LMI. But for β = 0.5 and P, Q, $X_e$ as function the performance $E_q$ by using Fuzzy LMI more stable than by using LMI.

For β = 0.5 and P, Q, $X_e$ as constant or as function, the overshooting of $E_{fd}$ by using Fuzzy LMI are larger than by LMI. The performance of $E_{fd}$ by using LMI more stable than by using Fuzzy LMI.

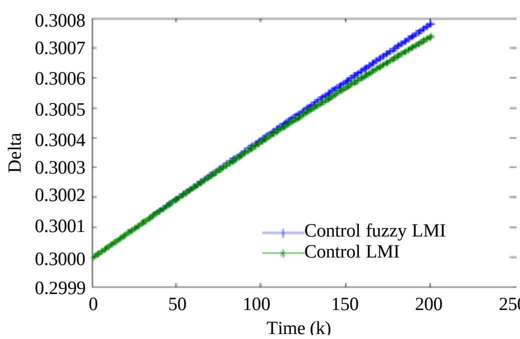


Fig. 15: The performance of δ (β = 0.01)

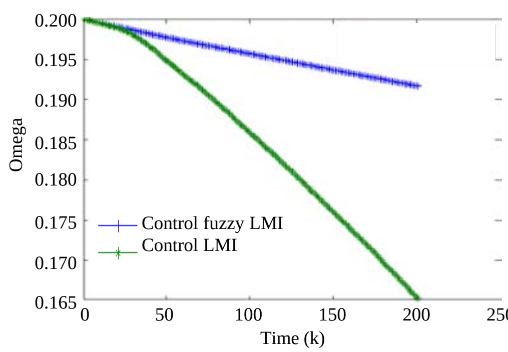


Fig. 16: The performance of ω (β = 0.01)

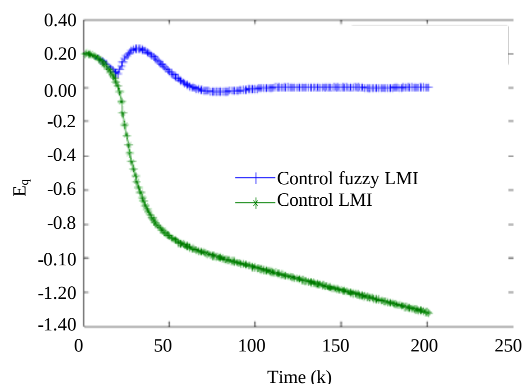


Fig. 17: The performance of $E_q$ (β = 0.01)

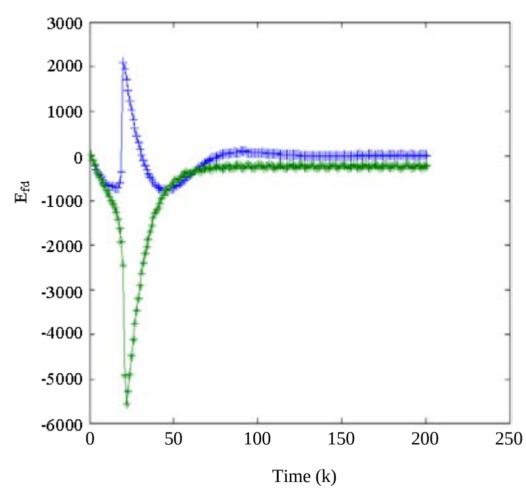


Fig. 18: The performance of $E_{fd}$ (β = 0.01)

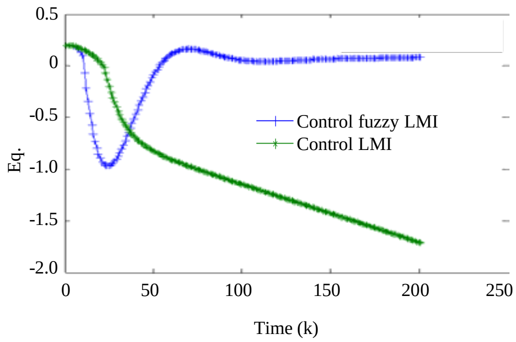


Fig. 19: The performance of $E_q$ for $\beta = 0.1$ P, Q, $X_e$ constant

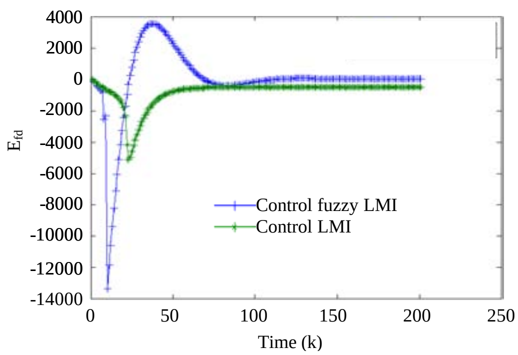


Fig. 20: The performance of $E_{fd}$ for $\beta = 0.1$; P, Q, $X_e$ constant

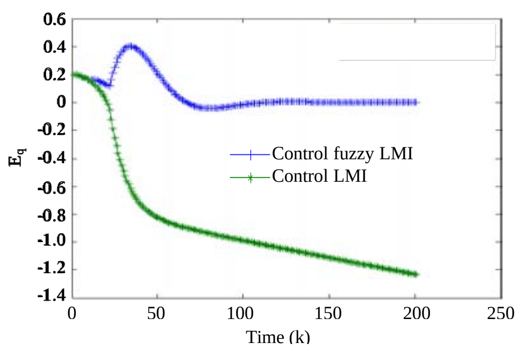


Fig. 21: The performance of $E_q$ for $\beta = 0.1$; P, Q, $X_e$ function

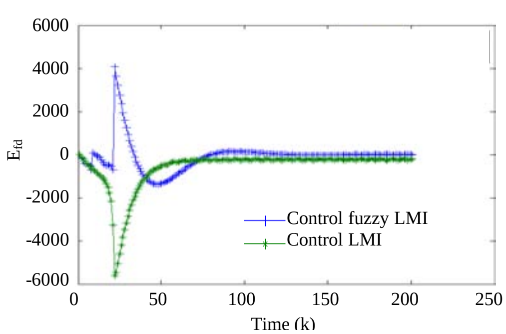


Fig. 22: The performance of $E_{fd}$ for $\beta = 0.1$; P, Q, $X_e$ function

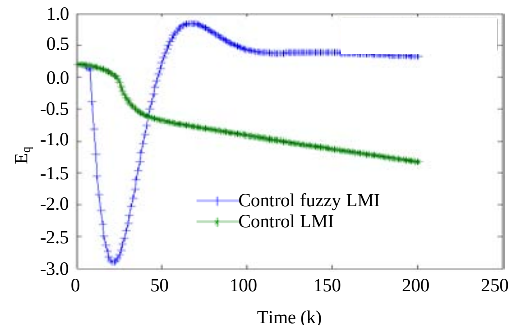


Fig. 23: The performance of $E_q$ for $\beta = 0.5$; P, Q, $X_e$ constant

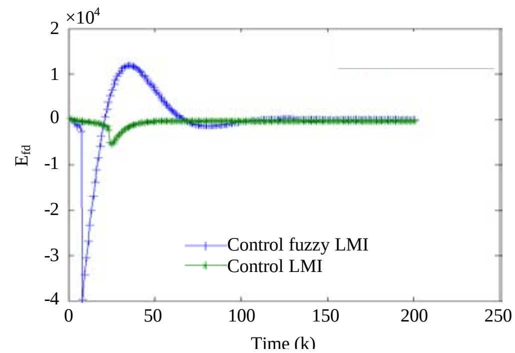


Fig. 24: The performance of $E_{fd}$ for $\beta = 0.5$; P, Q, $X_e$ constant

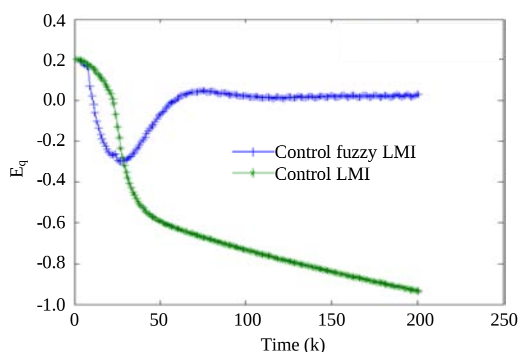


Fig. 25: The performance of $E_q$ for $\beta = 0.5$ P, Q, $X_e$ function

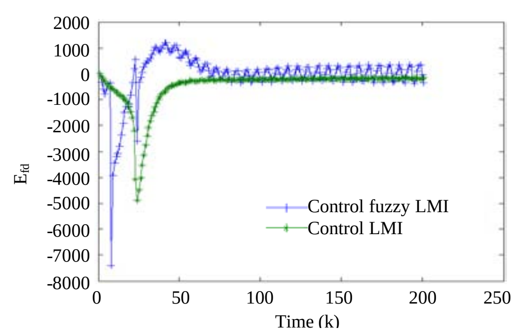


Fig. 26: The performance of $E_{fd}$ for $\beta = 0.5$ P, Q, $X_e$ function

## CONCLUSION

From the simulation result and discussion, it is conclude that: the fuzzy LMI and LMI output feedback controller have better performance of SMIB than Fuzzy Routh-Hurwitz and Fuzzy Pole Placement. The LMI and Fuzzy LMI output feedback gain:

$$K_i = \beta\left(\frac{1}{T_E}E^i_{fd} - dE^i_q\right)\frac{T_E}{\omega^i K_E}$$

With β = 0.01 give better performance than β = 0.5 and β = 0.5. The fuzzy LMI output feedback controller is better than LMI output feedback controller, either for P, Q, $X_e$ as constant (P = 0.8; Q = 0.2; $X_e$ = 0.8) or as function (P = 0.8 sin (t); Q = 0.2 sin (t); $X_e$ = 0.8 sin (t)). The fuzzy LMI output feedback controller is an control design method to enhance the performance of SMIB.

## NOMENCLATURE

| | | |
|---|---|---|
| $\delta$ | = | Angle |
| $\omega$ | = | Angular velocity |
| $E_q$ | = | Induced emf proportional to field current |
| $E_{fd}$ | = | Generator field voltage |
| $\omega_0$ | = | Initial angular velocity |
| $T_m$ | = | Mechanical torque |
| $T_E$ | = | Electrical torque |
| $I_q$ | = | Current on the axis q |
| $I_d$ | = | Current on the axis d |
| $x'_d$ | = | Generator synchronous reactances |
| $x_d$ | = | The d-axis synchronous reactances |
| $x_q$ | = | The q-axis synchronous reactances |
| M | = | Inertia coefficient |
| $T'_{do}$ | = | Open circuit direct axis transient |
| $K_E$ | = | Constant excitation |
| $V_{ref}$ | = | Reference value of generator field voltage |
| $V_T$ | = | Terminal voltage |
| $V_d$ | = | The voltage on the axis d |
| $V_q$ | = | The voltage on the axis q |
| $X_e$ | = | External reactive |
| P | = | Active power |
| Q | = | Reactive power |

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