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PSO FUZZY POLE PLACEMENT AND LMI OUTPUT FEEDBACK CONTROL TO IMPROVE THE STABILITY OF POWER SYSTEM

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Abstract

The stability of electrical supply is an important aspect in every industrial city so that the stability of the power system must be improved. The power system stabilizer has been done to Single Machine Infinite Bus (SMIB). Some method of control designs can be done for a linear system and for state feedback control. In this paper is presented the output feedback control and the fuzzy Takagi Sugeno model of SMIB is built to approach the nonlinearity of the SMIB System. The output feedback gain is determined by pole placement and to Linear Matrix Inequality (LMI) method. The parameters, which are contained on the output feedback gains, are tuned by using PSO to get the optimal performance. Some simulations have been done by using PSO fuzzy pole placement output feedback control and PSO fuzzy LMI output feedback control. From those simulations, it seems that PSO fuzzy pole placement output feedback control does not improve the stability performance of SMIB, but PSO fuzzy LMI output feedback control improve the stability performance of SMIB.

Keywords: Fuzzy output feedback control, LMI, PSO, Pole placement, Power system.

1. Introduction

The stability of electrical supply is an important aspect in every industrial city so that the stability of the power system must be increased. One type of power system is the Single Machine Infinite Bus (SMIB). The SMIB is a nonlinear system, so some researchers do linearization before design the control stability [1]. The control design methods have been done on SMIB such as Improved Swarm Optimization [2], robust control by using pole placement and Linear Matrix Inequality (LMI) [3, 4] and feedback linearization [5]. In the other method, the nonlinear system of SMIB is formed into a state space system and applied the fuzzy parameters, such as [6, 7]. In those papers, the output feedback control is applied to the fuzzy dynamic system. The LMI output feedback gain is derived and the parameters of feedback gains are determined by trial and error. Fuzzy logic controller is also applied on a wind turbine prototype with a pitch angle control [8].

The comparison between PI controlled Distributed Power Flow Controller (DPFC) and Fuzzy controlled DPFC have been applied to improve the stability of SMIB [9]. The comparison between PID, fuzzy, PSO-fuzzy and PSO fuzzy PID are applied to speed control of motor DC [10]. PID controller based adaptive PSO has been proposed as control design for a continuous stirred-tank reactor [11]. The parameters PSS of SMIB are also determined by the Hybrid Adaptive Chaotic Differential Evolution (HACDE), this method is compared with the DE and RD-PSO methods [12].

In this paper, it is applied PSO to determine the parameters of feedback gain of the output feedback control, such that the performance of SMIB is optimal. The first step, the nonlinear model of SMIB is written as state space form, then it is substituted the active, reactive and external reactive power as a fuzzy parameter into the state space system. Tanaka and Wang [13] mentioned that it used the Takagi Sugeno Fuzzy Model. The output control design by pole placement and LMI have applied the dynamic fuzzy system of SMIB and the parameters of feedback gain are tuned by using the PSO. The simulation has been done to compare the performance between PSO, Pole placement, LMI, PSO pole placement, PSO LMI, PSO fuzzy pole placement and PSO fuzzy LMI.

2. Fuzzy State Space Model

The SMIB has a nonlinear mathematical model [14]:

$$\dot{\delta} = \omega_0 \omega \tag{1}$$

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

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

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

where

$V_T = \sqrt{V_d^2 + V_q^2}; V_d = -X_e I_q + V_s \sin\delta; V_q = X_e I_q + V_s \cos\delta;$

$$P = \frac{E_q^{'}\ V_s}{x_{d\varepsilon}^{'}}\sin\delta;\ \ Q = \frac{E_q^{'}\ V_s}{x_{d\varepsilon}^{'}}\cos\delta - \frac{V_s^2}{x_{d\alpha}^{'}};$$

Usually, the feedback control design is applied to the linear system or the nonlinear system is changed into a linear system by doing direct linearization [6]. In this paper, the nonlinear system, Eqs. (1)-(4) is written as a state space system and it is applied fuzzy parameter to build the piecewise linear system. The state space system of SMIB is as follows:

$$\begin{bmatrix} \dot{\delta} \\ \dot{\omega} \\ \dot{E}_q^{'} \\ \dot{E}_{fd}^{'} \end{bmatrix} = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ 0 & A_1 & -D_1 & 0 \\ 0 & 0 & -B_1 & \frac{1}{T_0^{'}} \\ 0 & 0 & C_1 & -\frac{1}{T_E} \end{bmatrix} \begin{bmatrix} \delta \\ \omega \\ E_q^{'} \\ E_{fd}^{'} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{K_E}{T_E} \end{bmatrix} u_{pss} \tag{5}$$

where

$$A_1 = \frac{\left(T_m - (x_q - x_d^{'})I_d I_q\right)}{M\omega};$$

$$B_1 = \frac{1}{T_{d0}^{'}} + \frac{(x_d - x_d^{'})I_d}{T_{d0}^{'}E_q^{'}};$$

$$C_1 = \frac{K_E}{T_E E_q^{'}}(V_{ref} - V_T);$$

$$D_1 = \frac{Px'_{d\varepsilon}}{E_q^{'}X_e M} - \frac{V_d}{X_e M}$$

Equation 5 can be written as general state space system as follows:

$$\dot{X} = AX + Bu \tag{6}$$

where

$$X = \left[\delta \quad \omega \quad E_q^{'} \quad E_{fd}^{'}\right]^T;$$

$$A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ 0 & A_1 & -D_1 & 0 \\ 0 & 0 & -B_1 & \frac{1}{T_0^{'}} \\ 0 & 0 & C_1 & -\frac{1}{T_E} \end{bmatrix}; B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{K_E}{T_E} \end{bmatrix}$$

The state space system (Eq. 6) contains some parameters and variable such as *P*, *Q*, X_e , and $\omega, E_q^{'}$. Parameters *P*, *Q*, X_e are chosen as fuzzy parameters and it is applied Takagi-Sugeno fuzzy model [13]. Suppose, the interval fuzzy parameter are $P \in \left[P^- \quad P^+\right]$; $Q \in \left[Q^- \quad Q^+\right]$ and $X_e \in \left\lfloor X_e^{\ -} \quad X_e^{\ +}\right\rfloor$, then it is obtained the eight fuzzy rules.

Rule 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 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 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 output feedback control is applied to each system of eight rules, respectively. The fuzzy output feedback control is obtained by doing defuzzification. Suppose, it is defined as the member function of fuzzy.

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

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

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

and by defining:

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

Then defuzzification can be obtained as follows:

$$\dot{x} = \sum_{i=1}^{8} h_i (A_i x_i + Bu) \tag{7}$$

With output:

$$y = Cx_i \tag{8}$$

Control design of SMIB has been done by designing the controller for each fuzzy rule.

3. Fuzzy Output Feedback Control

In this paper, it is designed the output feedback control. It is defined control variable $u = -Ky$, where K is the output feedback gain and y is the output variable. The output variable (Eq. 8) is substituted into control variable u and then the control variable is substituted into Eq. 7, then the state space fuzzy system becomes:

$$\dot{x} = \sum_{i=1}^{8}\sum_{j=1}^{8} h_i (A_i - BK_j C_j) x_i \tag{9}$$

The fuzzy output feedback control design is obtained by determining output feedback gain K_j such that system in Eq. 9 is stable.

Tamaji and Robandi [7] mentioned that it has been determined the fuzzy output feedback gain by using pole placement method. From that paper, it is obtained that one of the poles is zero, suppose, $\lambda_4 = 0$ then the other poles are:

$$\lambda_2 = -\alpha\left(B_{1i} + \frac{1}{T_E} - A_{1i}\right);0 < \alpha < 1$$

$$\lambda_1 = -\frac{1}{2}(\rho + \lambda_2) \pm \frac{1}{2}\sqrt{(\rho + \lambda_2)^2 - 4\left(\lambda_2^2 + \rho\lambda_2 + \left(\frac{B_{1i}}{T_E^{'}} - \frac{C_{1i}}{T_0^{'}} - B_{1i}A_{1i} - \frac{A_{1i}}{T_E}\right)\right)},$$

where,

$$\rho = \left(B_{1i} + \frac{1}{T_E} - A_{1i}\right)$$

and

$$\lambda_3 = -\left(B_{1i} + \frac{1}{T_E} - A_{1i} + \lambda_1 + \lambda_2\right)$$

For those poles, the output feedback gain of pole placement is as follows:

$$K_{pj} = \left(\lambda_1\lambda_2\lambda_3 - A_{1i}B_{1i}\frac{1}{T_E^{'}} + A_{1i}\frac{C_{1i}}{T_0^{'}}\right)\frac{T_0^{'}T_E}{D_{1i}K_E} \tag{10}$$

According to Musyafa et al. [8], it also has been determined the output feedback gain by using LMI. The output feedback gain is as follows:

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

One of the poles in pole placement method (λ_2) contains the parameter α , and this parameter influences the feedback gain of pole placement output feedback control. The feedback gain of LMI output feedback control also contains a parameter β . Those parameters are great than zero and less than one. According to studies by Tamaji and Robandi [7] and Musyafa et al. [8], parameters α, β are determined by trial and error. In this paper, those parameters are determined by using the PSO method such that the performance of SMIB is optimal.

4. PSO Fuzzy Output Feedback Control

In this paper, parameters, which optimized are α for PSO fuzzy pole placement method and β for PSO fuzzy LMI method. There are two kinds of optimization. First, the PSO is applied in pole placement and fuzzy pole placement output feedback control and second, the PSO is applied in LMI and fuzzy LMI output feedback control.

4.1. PSO fuzzy pole placement output feedback control

The first simulation, PSO is applied to pole placement output feedback control. It is compared to the performance of SMIB by using pole placement, PSO, PSO pole placement and PSO fuzzy pole placement method. In the pole placement method, the output feedback gain is determined by using pole placement. In the PSO method, the output feedback gain is determined by PSO directly. In the PSO pole placement method, PSO is applied to optimise the parameter gain of Pole Placement output feedback control, and in the PSO fuzzy pole placement method, the PSO is applied to optimize the parameter gain of fuzzy pole placement output feedback control.

Suppose, the interval fuzzy parameters are:

$P \in [-0.2 \quad 1.8]; Q \in [-0.2 \quad 1.8]; X_e \in [-0.2 \quad 1.8]$ with P, Q, X_e = 0.8. For PSO method is chosen the interval optimization parameters $\alpha_i \in [a \quad b]$, where a = 0.00001; b = 0.01. The performance of SMIB by using pole placement method is presented in Figs. 1-4.

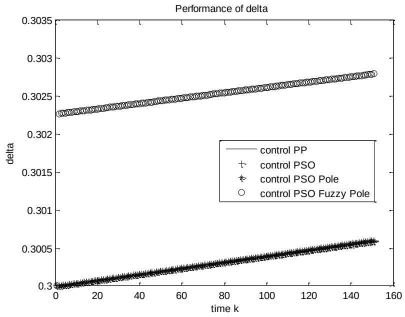

Fig. 1. Performance of δ by pole placement *a* = 0.00001; *b* = 0.01.

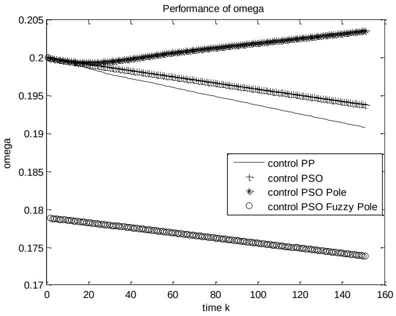

Fig. 2. Performance of ω by pole placement *a* = 0.00001; *b* = 0.01.

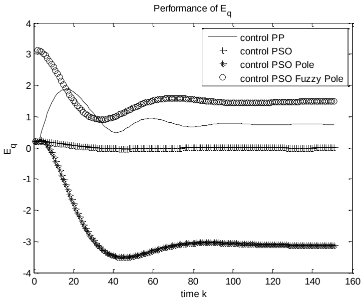

Fig. 3. Performance of E_q by pole placement *a* = 0.00001; *b* = 0.01.

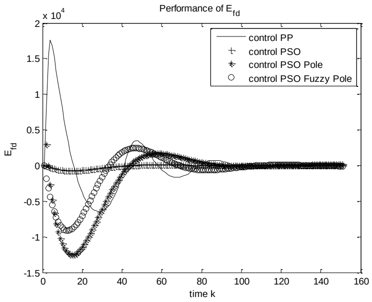

Fig. 4. Performance of E_{fd} by pole placement *a* = 0.00001; *b* = 0.01.

Figures 1-4 show that PSO, pole placement and PSO pole placement method give the same performance of δ, and almost the same performance of ω for PSO and pole placement, but the PSO fuzzy pole placement produce the larger amplitude for ω. For variables E_q and E_{fd}, the PSO fuzzy pole placement method gives more stable than PSO pole placement because it has a smaller amplitude. Therefore, for 0.00001; b = 0.01 the PSO fuzzy pole placement can improve the performance of SMIB.

The next simulation, it is tried to make larger interval optimize parameter. It is taken 0.00001; b = 0.01 and $\alpha_i \in [a \quad b]$. The performance of SMIB by using the PSO fuzzy pole placement method is presented in Fig. 5.

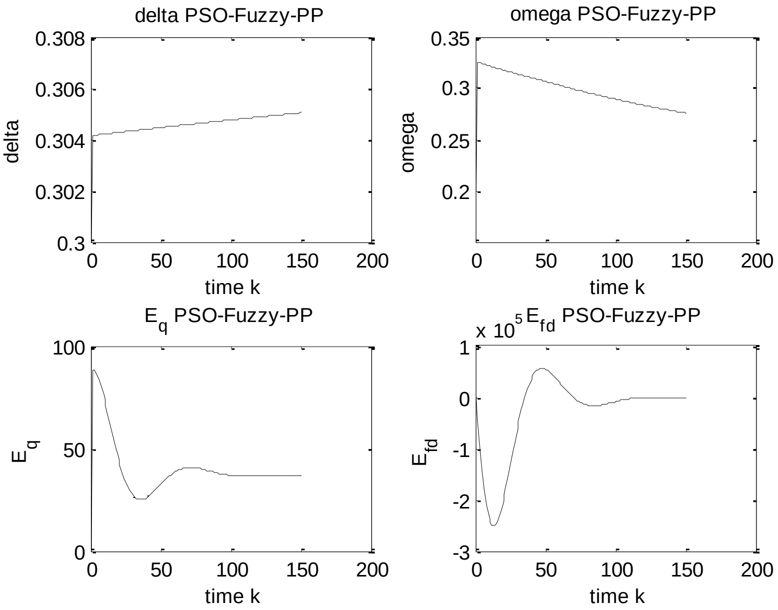

Fig. 5. Performance of SMIB by PSO fuzzy pole placement for *a* = 0.00001; *b* = 0.1.

For this interval parameter optimization (Fig. 5), PSO fuzzy pole placement cause variable δ increase directly to 0.3041 at short time and after that converges to 0.305, variable ω increase to 0.325 at a short time and then converges to 0.28. Variable E_q increase until 80 and then decrease until 40. There is an overshoot on a variable E_{fd} until -2.5×10^5 and then converges to zero. Therefore, the PSO pole placement and PSO fuzzy pole placement output feedback control cannot improve the stability performance of SMIB.

For the last simulation of pole placement output feedback control is taken the interval parameters optimization $\alpha_i \in [0.00001 \quad 0.5]$, or a = 0.00001; b = 0.5. The simulation result is presented in Fig. 6. Variable δ goes to 1.5×10^4, variable ω goes to 1.8×10^6. Variable E_q has overshot until 5.8×10^6 and variable E_{fd} has overshot until 5.8×10^6. Therefore, the PSO fuzzy pole placement cannot improve the stability performance of SMIB.

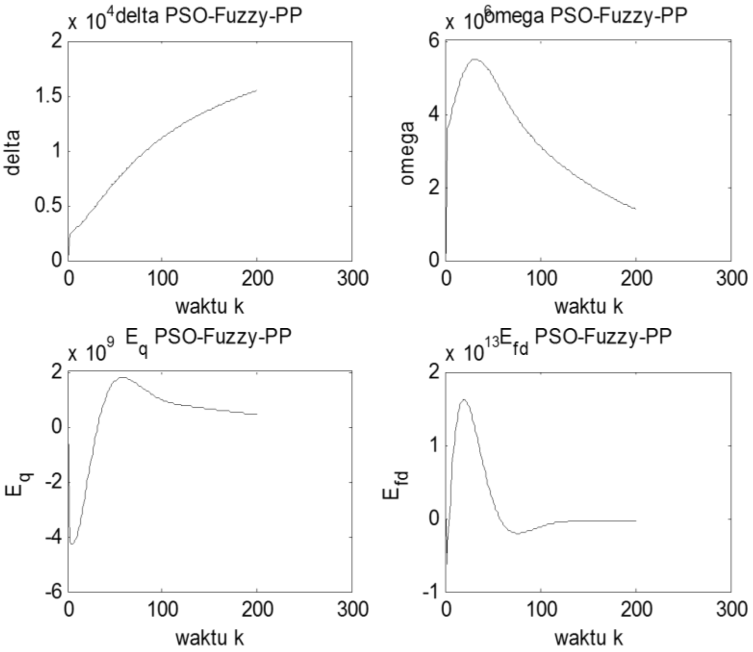

Fig. 6 Performance of SMIB by PSO fuzzy pole placement for *a* = 0.00001; *b* = 0.5.

From all those simulations, it can be concluded that PSO cannot be applied to pole placement and fuzzy pole placement output feedback control. The Pole Placement output feedback control produces a more stable performance of SMIB than the PSO fuzzy pole placement output feedback.

4.2. PSO fuzzy LMI output feedback control

The other method, which is proposed in this paper, is PSO fuzzy LMI output feedback control. In this method, the PSO is applied to determine the parameters of fuzzy LMI output feedback gain.

The performance of SMIB is compared with PSO, LMI and PSO LMI output feedback control. The interval fuzzy parameters are

$P \in [-0.2 \quad 1.8]; Q \in [-0.2 \quad 1.8]; X_e \in [-0.2 \quad 1.8]$ $P = 0.8; Q = 0.8 : X_e = 0.8$.

Such as in the pole placement method, the simulation has been done for three intervals of parameter optimization $\beta_i \in [0.00001 \quad 0.01]$ $\beta_i \in [0.00001 \quad 0.1]$ and $\beta_i \in [0.00001 \quad 0.5]$ or $a = 0.00001; b = 0.01$; $a = 0.00001; b = 0.1$ and *a* = 0.00001; *b* = 0.5.The first simulation, for $a = 0.00001; b = 0.01$, the performance of SMIB are presented on Figs. 7-10.

Figures 7-10 show that for this parameter interval, the PSO fuzzy LMI output feedback gives more stable the performance of SMIB although variable δ has a larger amplitude than PSO and LMI method.

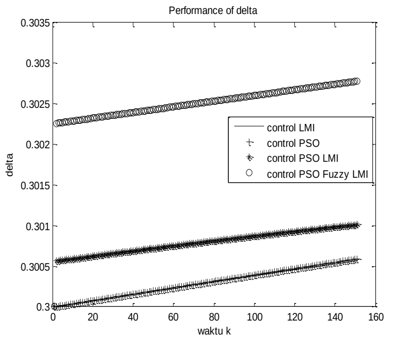

Fig. 7. Performance of δ by LMI for a = 0.00001; b = 0.01.

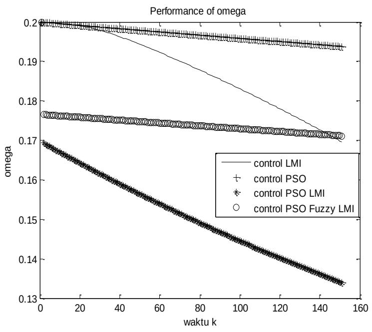

Fig. 8. Performance of ω by LMI for a = 0.00001; b = 0.01.

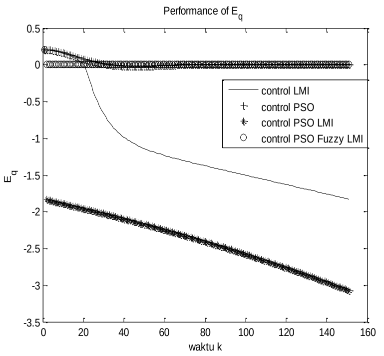

Fig. 9. Performance of E_q by LMI for a = 0.00001; b = 0.01.

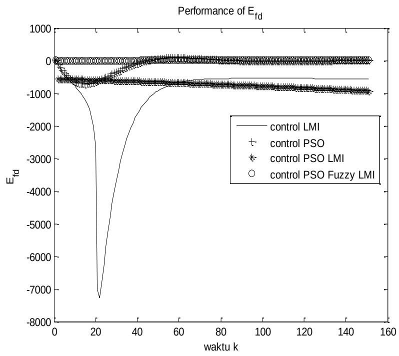

Fig. 10. Performance of E_{fd} by LMI for a = 0.00001; b = 0.01.

Variable ω converges to 0.171 and stable. Variables E_q, E_{fd} converge to zero. The performances of ω, Eq, E_{fd} by using the PSO fuzzy LMI method have the smallest amplitude than LMI, PSO, PSO LMI method.

From Fig. 11, it seems that the performance of SMIB by PSO fuzzy LMI output feedback is stable.

The second simulation, it is taken for a larger interval optimization parameter, $a = 0.00001; b = 0.1$. The performance of SMIB by using PSO fuzzy LMI is presented in Fig. 12.

For a = 0.00001; b = 0.1, PSO can be applied to fuzzy LMI output feedback control. The performance of SMIB by using PSO fuzzy LMI output feedback is more stable than the performance with parameter a = 0.00001; b = 0.01. Finally, the simulation is done for interval parameter optimization $\beta \in \begin{bmatrix} 0.00001 & 0.5 \end{bmatrix}$. By using PSO fuzzy LMI output feedback, the performance of SMIB is presented on Fig. 13.

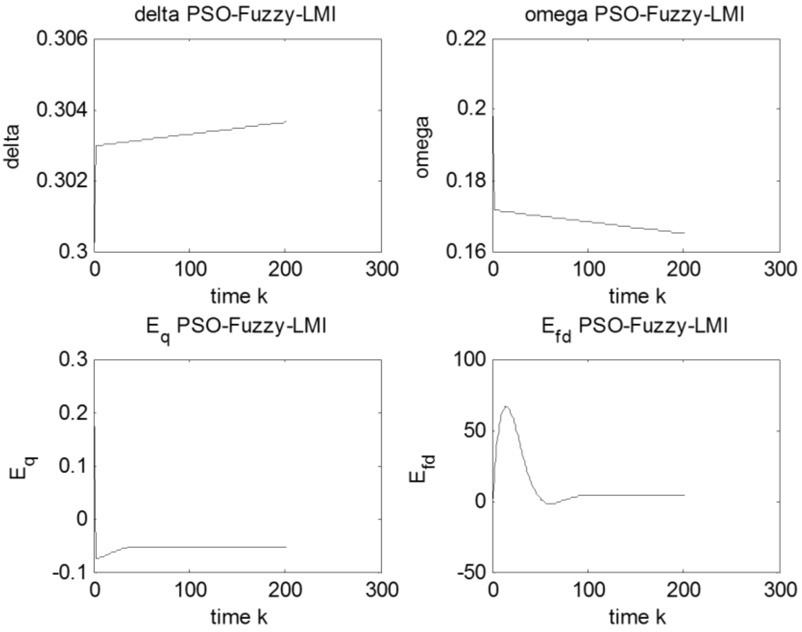

Fig. 11. Performance of SMIB by PSO fuzzy LMI for *a* = 0.00001; *b* = 0.1.

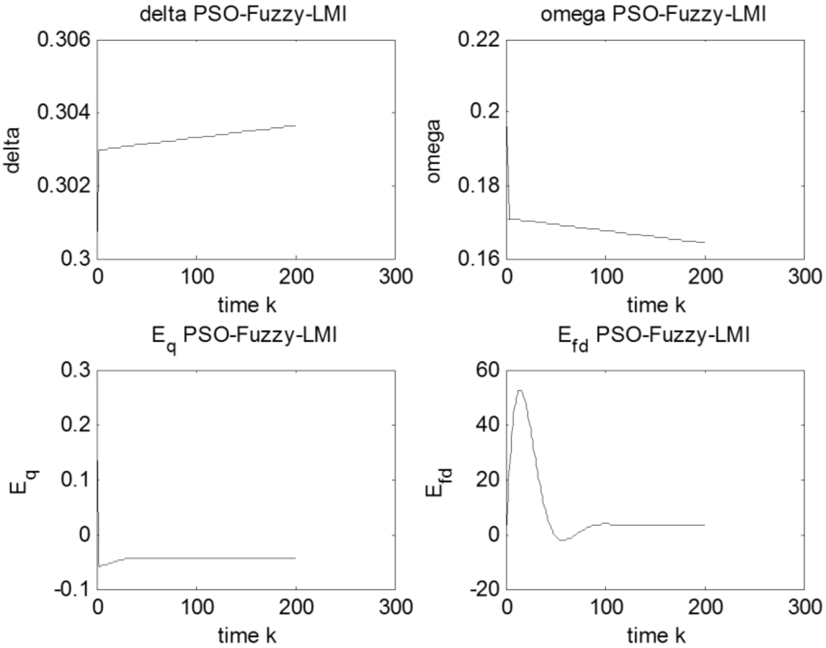

Fig. 12. Performance of SMIB by PSO fuzzy LMI output feedback for *a* = 0.00001; *b* = 0.1.

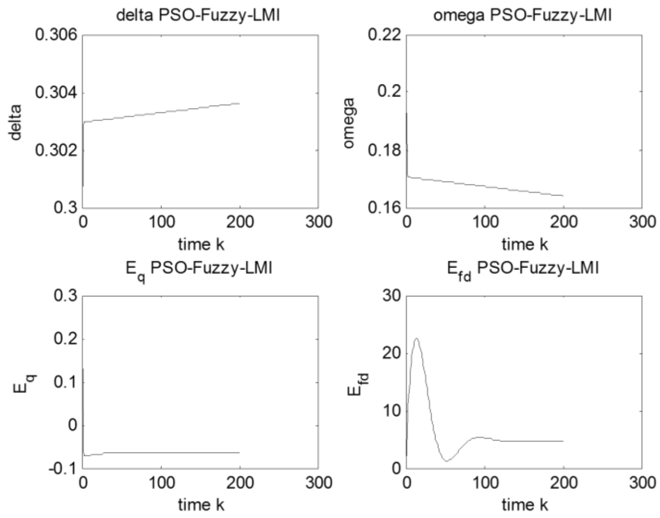

Fig. 13. Performance of SMIB by using PSO fuzzy LMI for *a* = 0.00001; *b* = 0.5.

By taking, $a = 0.00001; b = 0.5$, the PSO fuzzy LMI output feedback can improve the performance of SMIB. The performance of SMIB by using PSO fuzzy LMI for the parameter $a = 0.00001; b = 0.5$ is more stable (Fig. 13) than parameter $a = 0.00001; b = 0.1$ (Fig. 12) and $a = 0.00001; b = 0.01$ (Fig. 11).

For all simulation, the performance of SMIB after applying the output feedback control can be presented in Tables 1-4.

Table 1. Performance of δ.

$\alpha, \beta \in$ $[a \quad b]$	$a = 0.00001;$ $b = 0.01$	$a = 0.00001;$ $b = 0.1$	$a = 0.00001;$ $b = 0.5$
PSO	0.3006	0.3008	0.30052
Pole placement	0.3006	0.3008	0.30052
LMI	0.3006	0.3006	0.3006
PSO PP	0.3006	0.3008	0.3004
PSO LMI	0.301	0.301	0.301
PSO fuzzy PP	0.3028	0.305	100
PSO fuzzy LMI	0.3027	0.3027	0.3027

Table 2. Performance of ω.

$\alpha, \beta \in$ $[a \quad b]$	$a = 0.00001;$ $b = 0.01$	$a = 0.00001;$ $b = 0.1$	$a = 0.00001;$ $b = 0.5$
PSO	0.194	0.189	0.192
Pole placement	0.191	0.188	0.19
LMI	0.17	0.172	0.156
PSO PP	0.204	0.26	0.005
PSO LMI	0.135	0.02	0.103
PSO fuzzy PP	0.174	0.28	3×10^4
PSO fuzzy LMI	0.171	0.171	0.16

Table 3. Performance of E_q.

$\alpha,\beta\in[a\quad b]$	$a=0.00001$; $b=0.01$	$a=0.00001$; $b=0.1$	$a=0.00001$; $b=0.5$
PSO	0	0	0.014
Pole placement	2	0	0
LMI	-1.8	-1.4	-2.3
PSO PP	-3	-20	0
PSO LMI	-3	-2.8	-2.27
PSO fuzzy PP	3	40	1.5×10^{7}
PSO fuzzy LMI	0	0	-0.06

Table 4. Performance of E_{fd}.

$\alpha,\beta\in[a\quad b]$	$a=0.00001$; $b=0.01$	$a=0.00001$; $b=0.1$	$a=0.00001$; $b=0.5$
PSO	-8000	-1	0
Pole placement	1.7×10^{4}	0	0
LMI	-7000	-878.6	-500
PSO PP	1.3×10^{4}	0.6×10^{5}	1.1
PSO LMI	-800	0	0.4
PSO fuzzy PP	-0.9×10^{4}	-2.5×10^{5}	8×10^{10}
PSO fuzzy LMI	0	0	4

PSO can be applied to stabilise the SMIB (Tables 1-3), except on variable E_{fd}, there is overshoot until -800 (Table 4). The PSO fuzzy pole placement (PSO fuzzy PP) cause instability for variable E_{fd} and especially for the parameter, a = 0.00001; b = 0.5, the PSO fuzzy pole placement cause all variables of SMIB divergence.

The performance SMIB by using LMI, PSO LMI and PSO fuzzy LMI, are not dependent on the interval optimization parameters. The performance of each variable is almost the same between three interval optimization parameters. The performance of SMIB by using PSO fuzzy LMI has a smaller amplitude than other methods, so the PSO fuzzy LMI output feedback is more stable than the other methods.

5. Conclusions

Based on the simulation and discussion above, it can be concluded that:

- The nonlinearity of SMIB can be approximated by applying the fuzzy parameter such that, the system became piecewise linear.
- The performance of SMIB by using Pole Placement Output Feedback control more stable than by using PSO fuzzy pole placement output feedback control. Therefore, the PSO cannot be applied in pole placement output feedback control and fuzzy pole placement output feedback control.
- The PSO can improve the performance of SMIB by using LMI Output feedback control and fuzzy LMI output feedback control.
- The performance of SMIB by using PSO fuzzy LMI output feedback more stable than PSO fuzzy pole placement output feedback control.

- The PSO fuzzy LMI output feedback control gives the best performance of SMIB than other methods.

Further research:

- The other control design method can be proposed for further research such as fuzzy sliding mode control, fuzzy model predictive control and others
- The control design methods are stated in this paper can be applied for other power system models such as Multi Machine Infinite Bus (MMIB), guidance and control on automatic vehicle motion and other problem.

Nomenclatures

E_{fd}	Generator field voltage
E_q	Induced *emf* proportional to field current
I_d	Current on axis d
I_q	Current on axis q
K_E	Constant excitation
K_{Lj}	F feedback gain of LMI
K_{pj}	Feedback gain of pole placement
P	Active power
M	Inertia coefficient
Q	Reactive power
T'_{d0}	Open circuit direct axis transient
T_E	Electrical torque
T_m	Mechanical Torque
V_d	Vvoltage on axis d
V_q	Voltage on axis q
V_{ref}	Reference value of generator field voltage
V_T	Terminal voltage
X_e	Line reactance
x_d	D-axis synchronous reactance
x'_d	Generator synchronous reactance
x_q	Q-axis synchronous reactance

Greek Symbols

α	Parameter of pole placement output feedback gain
β	Parameter of LMI output feedback gain
δ	Angle
ω	Angular velocity
ω_o	Initial angular velocity

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