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 important aspect in every industrial city so that the stability of power system must be increased. In this paper is presented the control design of power system by applying the particle swarm optimization (PSO) into LMI fuzzy output feedback control method. Single Machine Infinite Bus is one of power system type. Here, the output feedback control method is applied to SMIB as case study. PSO is applied to Linear Matrix Inequality (LMI) fuzzy output feedback control and it is compared with PSO pole placement fuzzy output feedback control. Those output feedback gains are derived and the parameters which are contained on the output feedback gains are determine by using PSO to get the optimal performance. From those simulation, seem that PSO can't be apply to improve the stability performance of pole placement fuzzy output feedback control, but PSO can improve the performance of LMI fuzzy output feedback control.

Keywords: Power system, Pole Placement, LMI, PSO, Fuzzy Output Feedback control

1. Introduction

The stability of electrical supply is important aspect in every industrial city so that the stability of power system must be increased. One type of power system is Single Machine infinite Bus (SMIB). The SMIB is a nonlinear system, so that some researchers design the control stability by direct linearization of SMIB model before apply the control design method such as Improved Swarm Optimization [1], robust control by using pole placement and LMI [2]-[3], [4]-[5]. In the other method, the nonlinear system is formed into state space system and applied the fuzzy parameters, such as [6],[7]. In those papers, the output feedback control is applied to 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].

Nomenclatures

δ	angle
ω	angular velocity
E_q	induced *emf* proportional to field current
E_{fd}	generator field voltage
ω_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 reactance
x_d	d-axis synchronous reactance
x_q	q-axis synchronous reactance
M	inertia coefficient
T'_{d0}	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
K_{pj}	feedback gain of pole placement
K_{Lj}	feedback gain of LMI

The comparison between PID, Fuzzy, PSO-Fuzzy and PSO Fuzzy PID are applied to speed control of motor DC [9]. PID Controller Based Adaptive PSO has been proposed as control design for a continuous stirred-tank reactor [10]. The parameters PSS of SMIB also determined by the Hybrid Adaptive Chaotic Differential Evolution (HACDE), this method is compared with the DE and RD-PSO methods [11].

In this paper, it is applied PSO to determine the parameters of feedback gain such that the performance of SMIB is optimal. The first step, the non linear model of SMIB is written as state space form, then it is substituted the active, reactive and external reactive power as fuzzy parameter into the state space system. It is used Takagi Sugeno Fuzzy Model. The output control design by pole placement and LMI are 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. The Fuzzy State Space Model

The SMIB has a nonlinear mathematical model Mathematical model of SMIB is a nonlinear system [4],[12]

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

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 linear system or the nonlinear is approximated by linearization. In this paper, the nonlinear system is written as state space system and then it is applied fuzzy parameter to build the piecewise linear system. The state space system of SMIB is

$$\begin{bmatrix} \dot{\delta} \\ \dot{\omega} \\ \dot{E}_q^{'} \\ \dot{E}_{fd}^{'} \end{bmatrix} = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ 0 & A_1 & -D_1 & 0 \\ 0 & 0 & -B_1 & \frac{1}{T_0^{'}} \\ 0 & 0 & C_1 & -\frac{1}{T_E} \end{bmatrix} \begin{bmatrix} \delta \\ \omega \\ E_q^{'} \\ E_{fd}^{'} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{K_E}{T_E} \end{bmatrix} u_{pss} \qquad (2)$$

Where $A_1 = \frac{\left(T_m - (x_q - x_d^{'}) I_d I_q\right)}{M\omega}; B_1 = \left(\frac{1}{T_{d0}^{'}} + \frac{(x_d - x_d^{'}) I_d}{T_{d0}^{'} E_q^{'}}\right);$

$$C_1 = \frac{K_E}{T_E E_q^{'}}(V_{ref} - V_T); D_1 = \left[\left(\frac{P x'_{d\varepsilon}}{E_q^{'} X_e M} - \frac{V_d}{X_e M}\right)\right]$$

Equation 2 can be written as general state space system as follows:

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

where

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

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

The fuzzy parameters are P, Q, X_e and it is applied Takagi – Sugeno Fuzzy Model [13]. Suppose, the interval fuzzy parameter are

$P \in [P^- \quad P^+]; Q \in [Q^- \quad Q^+]$ and $X_e \in [X_e^- \quad X_e^+]$, 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 on each system of eight rules, respectively. The fuzzy output feedback control is obtained by doing defuzzyfication. By defining 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 follow:

$$\dot{x} = \sum_{i=1}^{8} h_i (A_i x_i + Bu) \qquad (3)$$

with output

$$y = Cx_i \qquad (4)$$

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

3. The Fuzzy Output Feedback Control

In this paper, it is design the output feedback control, it is mean, define the control variable $u = -Ky$.

The output variables (Eq. 4) are substituted into control variable u and Eq. 3 then the state space fuzzy system become

$$\dot{x} = \sum_{i=1}^{8}\sum_{j=1}^{8} h_i (A_i - BK_j C_j) x_i \tag{5}$$

The fuzzy output feedback control design is obtained by determining output feedback gain K_j such that system Eq. 5 is stable.

In [6] has been determined the fuzzy output feedback gain by using pole placement method. One of poles is zero, suppose $\lambda_4 = 0$, then the others poles are

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

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

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

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

And the output feedback gain of pole placement is

$$K_{pj} = \left(\lambda_1\lambda_2\lambda_3 - A_{1i}B_{1i}\frac{1}{T_E^{'}} + A_{1i}\frac{C_{1i}}{T_0^{'}}\right)\frac{T_0^{'}T_E}{D_{1i}K_E} \tag{6}$$

and in [7], it also has been determined the output feedback gain by using LMI. The output feedback gain is

$$K_{Lj} = \beta\left(\frac{1}{T_E}E_{fd} - dE_q\right)\frac{T_E}{\omega K_E}; 0 < \beta < 1 \tag{7}$$

One of poles in pole placement method (λ_2) contains 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 parameter β .

In [6] and [7], parameters α, β are determined by trial and error. In this paper, those parameters are determined by using PSO method such that the performance of SMIB is optimal.

4. The PSO Fuzzy Output Feedback Control

In previous research [6] and [7], show that the determination of parameter α, β by using trial and error method, give the performance of SMIB is not optimal. Therefore, it is proposed the PSO Fuzzy Output feedback control, the PSO which is applied to determine the parameter α, β in Fuzzy Pole Placement method and Fuzzy LMI method. So that, 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 The PSO Fuzzy Pole Placement Output Feedback Control

The first simulation, it is applied PSO into pole placement output feedback control. It is compared the performance of SMIB using Pole Placement, PSO, PSO Pole Placement and PSO Fuzzy Pole Placement method. The Pole placement method is the output feedback control, which the feedback gain is determined by using pole placement. The PSO method is the feedback of output feedback control is determined by PSO directly, the PSO pole placement method is mean, the PSO is apply to optimize the parameter gain of Pole Placement output feedback control, and the PSO Fuzzy pole placement method is mean, the PSO is apply 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 $P = Q = X_e = 0.8$ the interval optimization parameters
$\alpha_i \in [a \quad b]; \beta_i \in [a \quad b]$, where
$a = 0.00001$; $b = 0.01$. The performance of SMIB are presented on figure 1-4

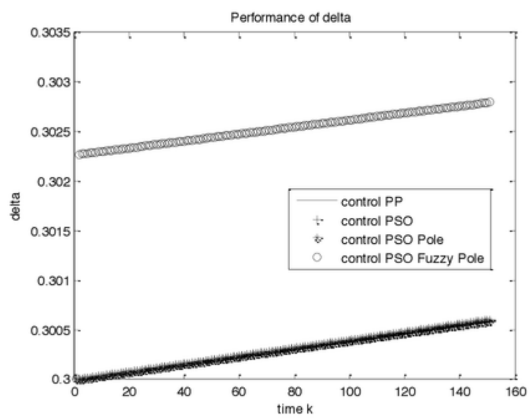


Fig. 1. The Performance of δ by Pole Placement $a = 0.00001; b = 0.01$

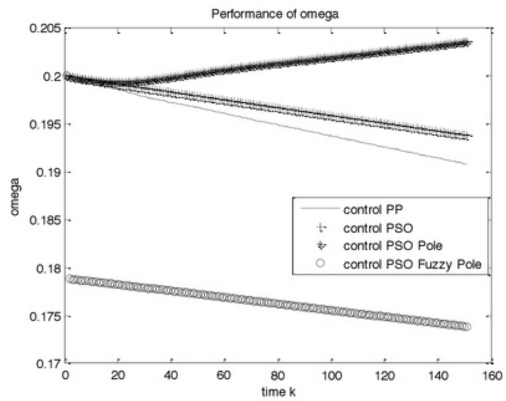


Fig. 2. The Performance of ω by Pole Placement $a = 0.00001; b = 0.01$

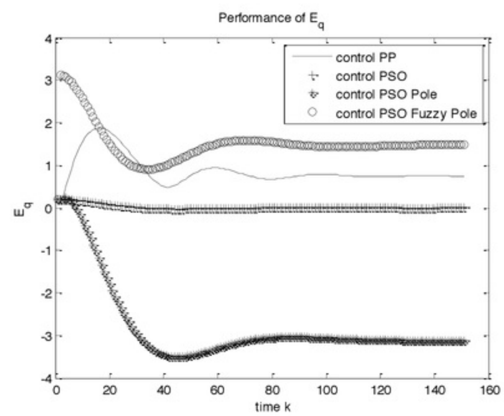


Fig. 3. The Performance of E_q by Pole Placement $a = 0.00001; b = 0.01$

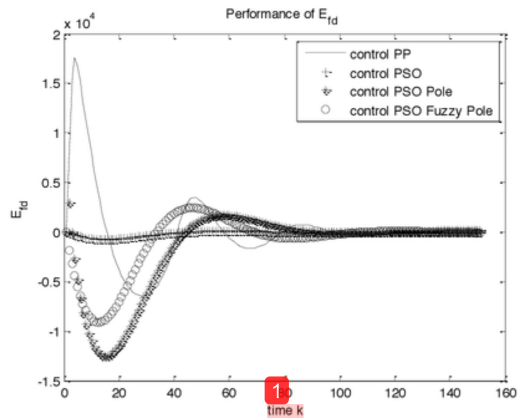


Fig. 4. The Performance of E_{fd} by Pole Placement $a = 0.00001; b = 0.01$

Figure 1-4 shows that PSO, Pole Placement and PSO Pole Placement 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 give more stable than PSO Pole Placement. So, for $a = 0.00001; b = 0.01$ the PSO Fuzzy Pole Placement can improve the performance of SMIB.

The next simulation, it is tried to make a larger interval optimize parameters. It is taken $a = 0.00001; b = 0.1$ and $\alpha_i \in [a \quad b]$; $\beta_i \in [a \quad b]$.
The performance of SMIB is presented on Figure 5-9.

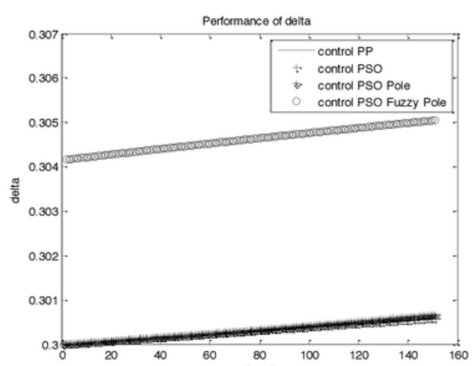


Fig. 5. The Performance of δ by pole placement for $a = 0.00001; b = 0.1$

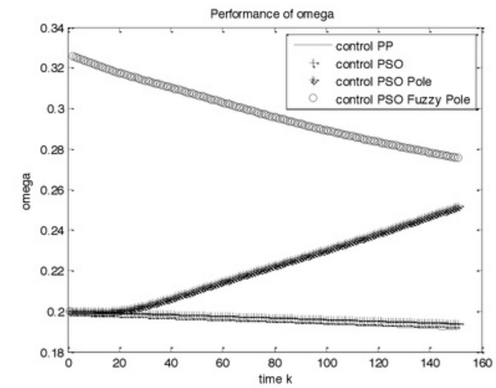


Fig. 6. The Performance of ω by pole placement for $a = 0.00001; b = 0.1$

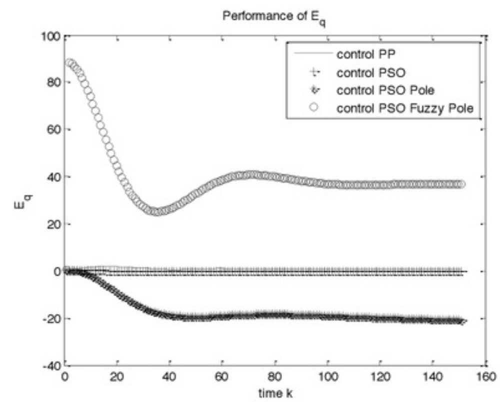


Fig. 7. The Performance of E_q by pole placement for $a = 0.00001; b = 0.1$

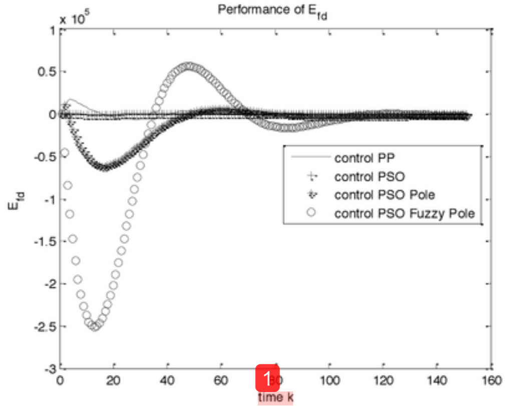


Fig. 8. The Performance of E_{fd} by pole placement for $a = 0.00001; b = 0.1$

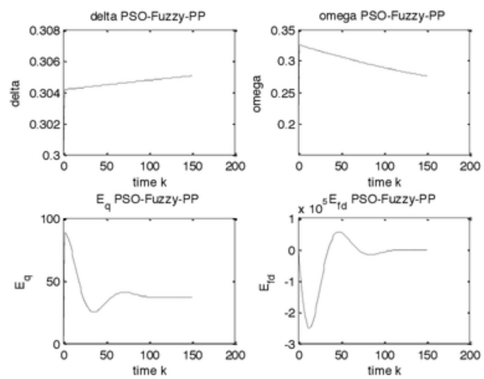


Fig. 9. The Performance of SMIB by PSO Fuzzy Pole Placement for $a = 0.00001; b = 0.1$

For this interval optimize parameter, PSO, Pole placement, have the same performance of δ, ω, control PSO Pole Placement cause the performance of ω tends to 0.25, variable E_q tend to -20 and variable E_{fd} have overshooting until -0.6×10^5. PSO Fuzzy pole placement produce the performance 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 variable E_{fd} until -2.5×10^5 and converges to zero. For $a = 0.00001; b = 0.1$, PSO can't improve the performance of SMIB by using pole placement method, either with Fuzzy or without fuzzy.

The last simulation for Pole Placement output feedback control is taken the interval parameters optimization $\alpha_i \in [0.00001 \quad 0.5]$; $\beta_i \in [0.00001 \quad 0.5]$ or $a = 0.00001; b = 0.5$. In this simulation are obtained that PSO can't be applied in the Fuzzy Pole Placement output feedback control because the performance of SMIB become divergence and have large amplitude (Figure 10-13).

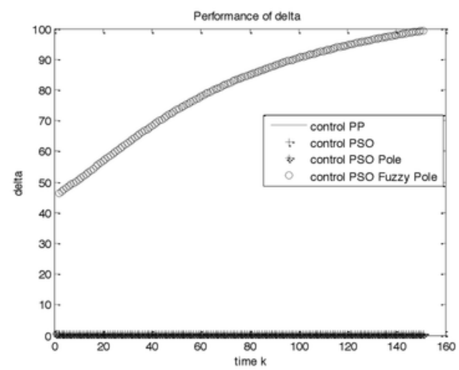
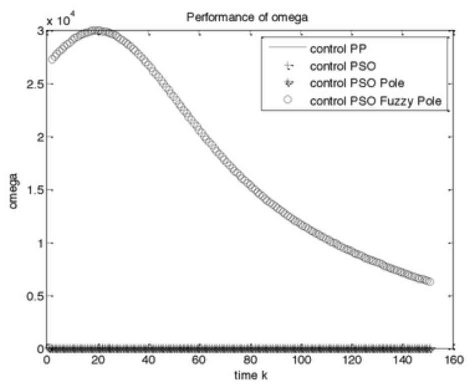


Fig. 10. The Performance of δ by Pole Placement for $a = 0.00001; b = 0.5$



Fig/ 11/ The Performance of ω by Pole Placement for $a = 0.00001; b = 0.5$

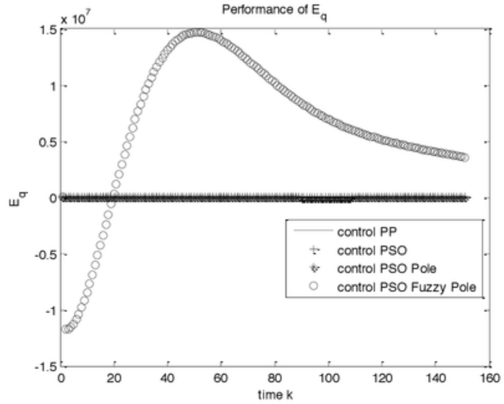


Fig. 12/ The Performance of E_q by Pole Placement for $a = 0.00001; b = 0.5$

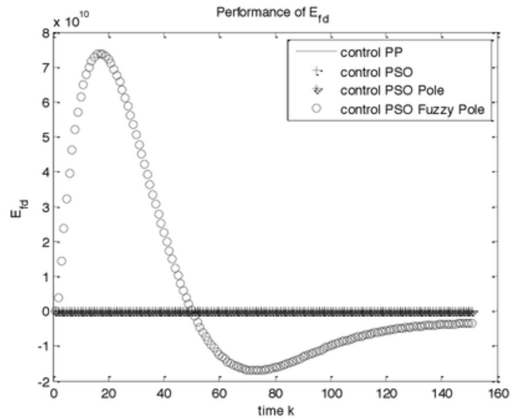


Fig. 13/. The Performance of E_q by Pole Placement for $a = 0.00001; b = 0.5$

From those simulations, it can be conclude that PSO can't be applied to Pole Placement and Fuzzy Pole Placement Output Feedback Control. The Pole Placement output feedback control produces more stable performance of SMIB.

4.2. The 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

$P \in [-0.2 \quad 1.8]; Q \in [-0.2 \quad 1.8]; X_e \in [-0.2 \quad 1.8] \quad P = 0.8; Q = 0.8 : X_e = 0.8$.
Such as in the pole placement method the simulation has been done for three interval of parameter optimization $\alpha_i \in [0.00001 \quad 0.01]; \beta_i \in [0.00001 \quad 0.01]$
$\alpha_i \in [0.00001 \quad 0.1]; \beta_i \in [0.00001 \quad 0.1]$ and
$\alpha_i \in [0.00001 \quad 0.5]; \beta_i \in [0.00001 \quad 0.5]$, 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 Figure 14-17

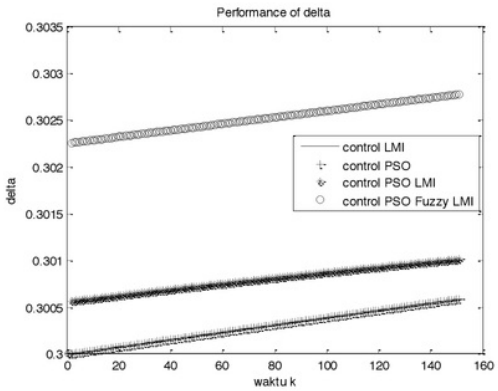


Fig. 14. Performance of δ by LMI for $a = 0.00001; b = 0.01$

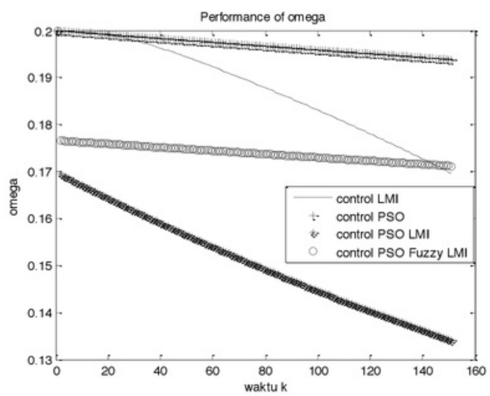


Fig. 15. Performance of ω by LMI for $a = 0.00001; b = 0.01$

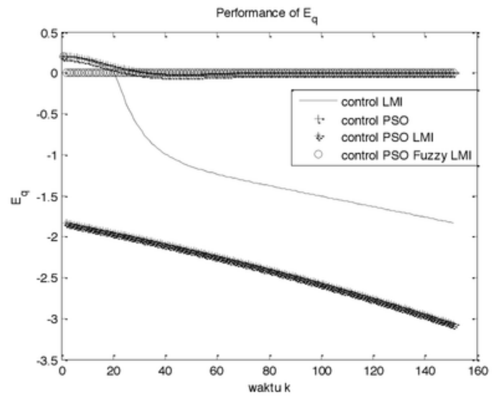


Fig. 16. Performance of E_q by LMI for $a = 0.00001; b = 0.01$

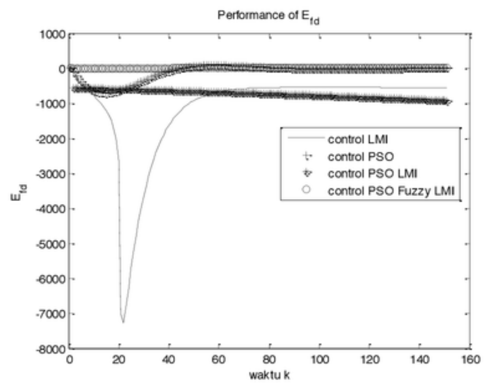


Fig. 17. Performance of E_{fd} by LMI for $a = 0.00001; b = 0.01$

Figure 14-17 show that by using PSO Fuzzy LMI output feedback, the performance of SMIB more stable although variable δ have larger amplitude than PSO and LMI method. 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. So, for $a = 0.00001; b = 0.01$, PSO fuzzy LMI output feedback can improve the performance of SMIB.

The second simulation, it is taken larger interval optimization parameter, $a = 0.00001; b = 0.1$.

The performance of SMIB are presented in Figure 18-22.

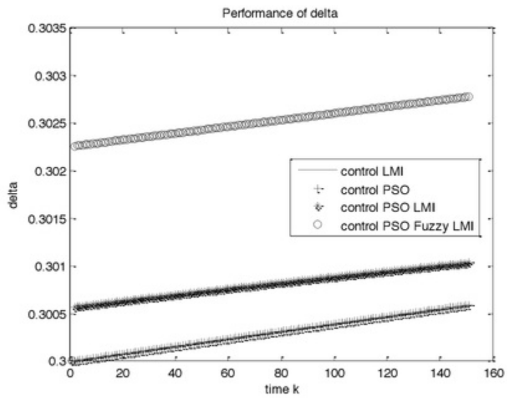


Fig. 18. Performance of δ by LMI for $a = 0.00001; b = 0.1$

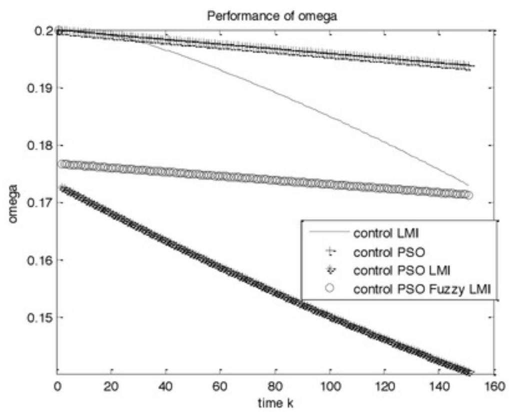


Fig. 19. Performance of ω by LMI for $a = 0.00001; b = 0.1$

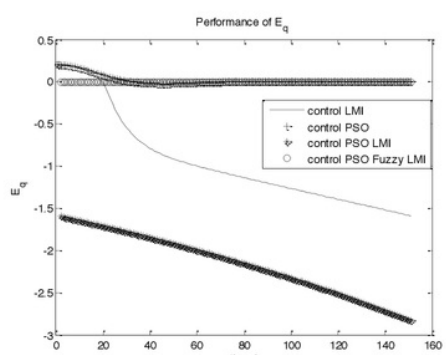


Fig. 20. Performance of E_q by LMI for $a = 0.00001; b = 0.1$

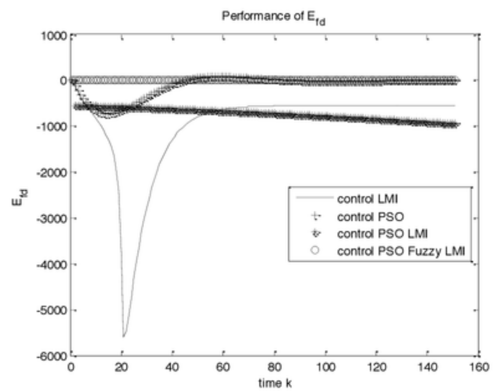


Fig. 21. Performance of E_{fd} by LMI for $a = 0.00001; b = 0.1$

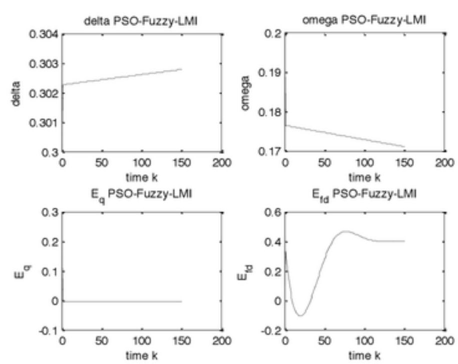


Fig. 22 The performance of SMIB by PSO Fuzzy LMI output feedback for $a = 0.00001; b = 0.1$

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 more stable than by using LMI, PSO and PSO LMI method.

Finally, the simulation is done for interval optimization parameter
$\alpha \in [0.00001 \quad 0.5]; \beta \in [0.00001 \quad 0.5]$
The performance of SMIB are presented on Figure 23-26 .

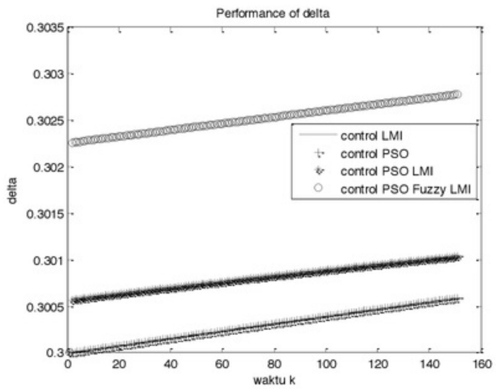


Fig. 23. Performance of δ by LMI for $a = 0.00001; b = 0.5$

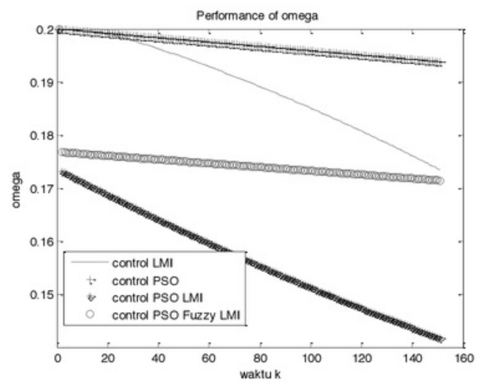


Fig. 24. Performance of ω by LMI for $a = 0.00001; b = 0.5$

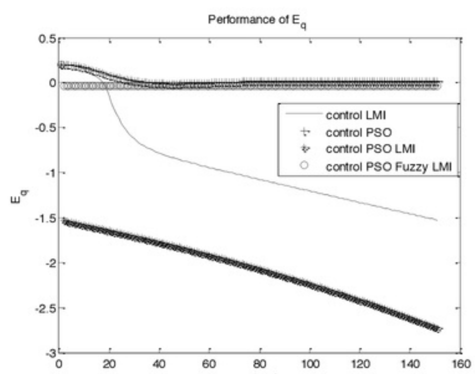


Fig. 25. Performance of E_q by LMI for $a = 0.00001; b = 0.5$

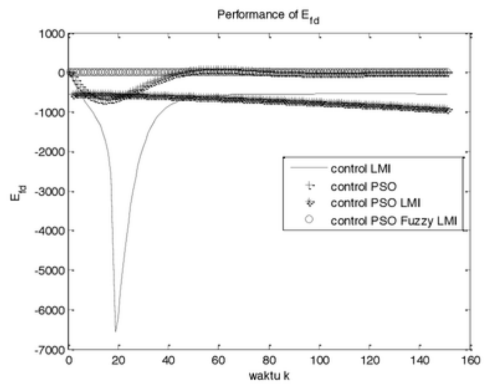


Fig. 26. Performance of E_{fd} by LMI for $a = 0.00001; b = 0.5$

By taking, $a = 0.00001; b = 0.5$, the PSO Fuzzy LMI output feedback can improved the performance of SMIB, although variable δ by using PSO Fuzzy LMI method has larger amplitude than PSO, LMI and PSO LMI method (The difference is 0.0020 or 0.667%) and variable ω by using PSO Fuzzy LMI is larger than LMI and PSO method, but smaller than PSO LMI method.

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

Table 1. The 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. The 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	0.19
Pole Placement	0.191	0.188	0.19
LMI	0.17	0.172	0.172
PSO PP	0.204	0.26	0.005
PSO LMI	0.135	0.02	0.1
PSO Fuzzy PP	0.174	0.28	3×10^4
PSO Fuzzy LMI	0.171	0.171	0.17

Table 3. The 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
Pole Placement	2	0	0
LMI	-1.8	-1.4	-1.5
PSO PP	-3	-20	0
PSO LMI	-3	-2.8	-2.8
PSO Fuzzy PP	3	40	1.5×10^7
PSO Fuzzy LMI	0	0	0

Table 4. The 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	-800	0
Pole Placement	1.7×10^4	0	0
LMI	-7000	-5500	-500
PSO PP	1.3×10^4	0.6×10^5	0
PSO LMI	-800	1	0
PSO Fuzzy PP	-0.9×10^4	-2.5×10^5	8×10^{10}
PSO Fuzzy LMI	0	0	0

PSO can be applied to stabilize the SMIB, except on variable, E_{fd} , there are overshoot until -800. There are instability performance of SMIB by using PSO Fuzzy Pole Placement, and for parameter, $a=0.00001; b=0.5$, all variables of SMIB are divergence. The performance SMIB by using LMI, PSO LMI and PSO Fuzzy LMI is not depending on the interval optimization parameters. The performance of each variable is almost same between three interval optimization parameters. The performance of SMIB by using PSO Fuzzy LMI is more stable than the others method, because produce the same amplitude for all variable and all parameters optimization.

5. Conclusion

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

1. The nonlinearity of SMIB can be approximated by applied fuzzy parameter, such as the system became piecewise linear.
2. The PSO can't be applied in pole placement output feedback control and Fuzzy pole placement output feedback control because the performance of SMIB by using Pole Placement Output Feedback control more stable than by using PSO Fuzzy Pole Placement Output Feedback Control
3. The PSO Fuzzy Pole Placement Output feedback control can't be applied to design the controller of SMIB, because this method causes the instability of system, especially for parameter $a=0.00001; b=0.5$.
4. The PSO can be applied to LMI Output feedback control and Fuzzy LMI output feedback control and the performance of SMIB more stable

5. The PSO Fuzzy LMI Output Feedback control can improve the stability of SMIB.
6. The PSO Fuzzy LMI Output Feedback control give the best performance of SMIB than others methods.

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