Comparison of Fuzzy Logic Based and Conventional Power System Stabilizer for Damping of Power System Oscillations

K. Prasertwong, and N. Mithulananthan

Abstract— *This paper presents some interesting simulation results of a single machine infinite-bus system, with fuzzy logic based power system stabilizer (FLPSS). A comparison is also made between the FLPSS and conventional power system stabilizer (CPSS). In CPSS, one input signal, i.e. rotor speed deviation is used. However, in FLPSS, two input signals were used. The control input signals used in FLPSS are real power deviation and derivative of power deviation. It was found that FLPSS performs better than CPSS. However different operating points need to considered in both the cases to make a firm conclusion. Apart from its ability to give satisfactory operation at different operating conditions, it is possible to feed multi signal as control inputs in FLPSS. FLPSS design can be improved further, by considering fuzzification and defuzzification methods and changing other parameters.*

Keywords— **Fuzzy logic controller, Power System Oscillations, Power System stability, Power System Stabilizer.**

1. INTRODUCTION

Oscillations of small magnitude and low frequency often persisted for long periods of time and in some cases presented limitations on power transfer capability. Power system stabilizers were developed to aid in damping these oscillations via modulation of the generator excitation [1].

The basic function of a power system stabilizer is to extend stability limits by modulating generator excitation to provide damping to the oscillations of synchronous machine rotors relative to one another. These oscillations of concern typically occur in the frequency range of approximately 0.2 to 2.5 Hz, and insufficient damping of these oscillations may limit the ability to transmit power. To provide damping, the stabilizer must produce a component of electrical torque on the rotor which is in phase with speed variations [2], [3], [4], [5], [6].

Tuning of supplementary excitation controls for stabilizing system modes of oscillation has been the subject of much research during the past 20 to 25 years. Two basic tuning techniques have been successfully utilized with power system stabilizer applications: phase compensation and root locus. Phase compensation consists of adjusting the stabilizer to compensate for the phase lags through the generator, excitation system, and power system such that the stabilizer path provides torque changes which are in phase with speed changes. This is the most straightforward approach, easily understood and implemented in the field, and the most widely used. Synthesis by root locus involves shifting the eigenvalues associated with the power system modes of oscillation by adjusting the stabilizer pole and zero locations in the s-plane. This approach gives additional insight to performance by working directly with the closed-loop characteristics of the system, as opposed to the open-loop nature of the phase compensation technique, but is more complicated to apply, particularly in the field.

Fuzzy logic is much closer in spirit to human thinking and natural language than the traditional logical systems. Basically, it provides an effective means of capturing the approximate, inexact nature of the real world [7]. Viewed in this perspective, the essential part of the fuzzy logic controller (FLC) is a set of linguistic control rules related by the dual concepts of fuzzy implication and the compositional rule of inference. In essence, then, the FLC provides an algorithm which can convert the linguistic control strategy based on expert knowledge into an automatic control strategy. Experience shows that the FLC yields results superior to those by conventional control algorithms. In particular, the methodology of the FLC appears very useful when the processes are too complex for analysis by conventional quantitative techniques or when the available sources of information are interpreted qualitatively, inexactly, or uncertainly. Thus fuzzy logic control may be viewed as a step toward a rapprochement between conventional precise mathematical control and human-like decision making.

The fuzzy logic based PSS was proposed in [8] used two real-time measurements $\Delta\omega$ (generator speed deviation) and $\Delta\dot{\omega}$ (acceleration) as the input signal. In this paper, however, FLPSS uses active power deviation and its derivative as the input signals.

The power system stabilizer is a supplementary control system, which is often applied as part of the excitation control system [4]. The basic function of the PSS is to apply a signal to the excitation system; creating electrical torque's that damp out power oscillations. Since the primary function of the PSS is to add damping to the power oscillation, basic control theory would indicate that any signal in which the power oscillations are

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observable is a good candidate for input signal.

When consider the nature of the two input signals, speed and electrical power [4]. In general they both have some steady-state value, and may change slowly over long periods of time. For this reason, as is normally done in most PSS designs, a high pass filter is applied to both inputs. This filter is also called a washout filter, since it "washes out" or eliminates the low frequency signals. The form of the washout filter is as follows:

$$\frac{sT_w}{(1+sT_w)}$$

where T_w is the washout time constant, normally set in the range of 2 to 15 seconds. This gives a break frequency of $1/T_w$ rad/sec. If T_w is 10 seconds, then the filter breakpoint occurs 0.0159 Hz, well below intertie mode frequencies.

In reference [11], the author was discuss the experience in assigning PSS projects in an undergraduate control design course to provides students with a challenging design problem using root-locus, frequency-domain, and state-space methods. In this paper proposed an advanced techniques using fuzzy logic controller for damp power system oscillation. Thus parameter of conventional PSS is obtained in [11]. The MATLAB package, with the Fuzzy Logic Toolbox and Simulink, was used for the design [13].

2. POWER SYSTEM MODEL

A single-machine infinite-bus system in (Fig. 1) was used as the design model [11], usually used as the first step in designing an excitation system control for a power plant delivering an electric power [12]. The machine model includes sub-transient effects, and the field voltage actuator is a solid state rectifier. The machine delivers the electrical power P_e to the infinite bus. The voltage regulator controls the input u to a solid-state rectifier excitation, which provides the field voltage to maintain the generator terminal voltage V_{term} at a referenced value V_{ref}. The states for the machine are its rotor angle δ, its speed ω, and its direct- and quadrature-axis fluxes E'_q, ψ_d, E'_d, and ψ_q. The exciter is modeled with the voltage state V_R. All of the variables are normalized on a per-unit (p.u.) basis, except for δ which is in radians.

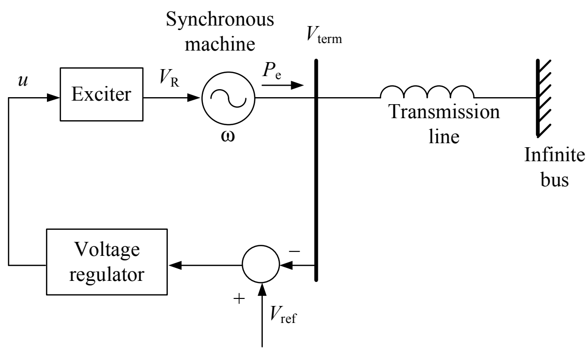

Fig.1. Single-machine infinite-bus system.

The power system model is linearized at a particular equilibrium point to obtain the linearized system model given in the state-space form

$$\Delta\dot{x} = A\Delta x + B\Delta u,\ \Delta y = C\Delta x \tag{1}$$

where Δ denotes the perturbation of the states, input, and outputs from their equilibrium values, with

$$x = \begin{bmatrix}\delta & \omega & E'_q & \psi_d & E'_d & \psi_q & V_R\end{bmatrix}^T \tag{2}$$

$$y = \begin{bmatrix}V_{term} & \omega & P_e\end{bmatrix}^T \tag{3}$$

The matrices for (1) derived from typical machine parameters are given in Appendix A. The dominant poles of (1) are the real poles s = -0.105 associated with the field voltage response, and the electromechanical (swing) mode $s = -0.479 \pm j9.33$ with a small damping ratio ξ = 0.0513, representing the oscillation of machine against the infinite bus.

The input signal to a speed-input PSS is derived from the machine speed passed through a washout filter and several banks of torsional filters. The washout (derivative) filter $10s/(10s + 1)$ is a high-pass filter having a dc gain of 0, such that in steady state, the PSS path is not active. The aggregate phase lag effect of the torsional filters is represented by:

$$G_{tor}(s) = \frac{1}{1+0.061s+0.0017s^2} \tag{4}$$

The speed input stabilizer consists of a washout stage, a double lead/lag stage, and a filter to attenuate high frequency components [1].

Convention control design

Starting from (1), we were required to first use the terminal bus voltage signal V_{term} to design a high-gain voltage regulator (VR). Because the VR destabilized the swing mode, a PSS using the machine speed deviation signal was used to add damping to the swing mode. The feedback control system block diagram implemented in Simulink is shown in Fig.2.

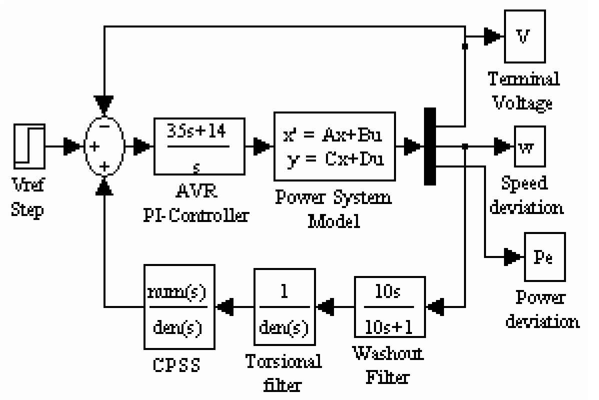

Fig.2. Simulink diagram of conventional power system stabilizer.

The process was specified in several tasks [11]:

(R1) For a 0.1-p.u. step in V_{ref}, simulate the V_{term} response of the open-loop system equation. (1) up to 10 s. Then with the PSS-loop open, repeat the simulation for equation (1) controlled by a proportional VR, $K_V(s) = K_p$ with $K_p = 10, 20, \ldots, 50$.

(R2) Make a root-locus plot of the voltage regulation loop using the proportional controller and find the gain K_u when the lightly damped swing mode becomes unstable.

(R3) Apply a PI controller for the VR

$$K_V(s) = K_{PI}(s) = K_P(1 + \frac{K_I}{s}) \tag{5}$$

and plot the closed-loop V_{term} response to a 0.1-p.u. V_{ref} step input. Select the parameters from $0 < K_p < K_u$ and $0.1 < K_I < 10$ such that the rise time t_r is less than 0.5s and the overshoot M_p is about 10%. These specifications reflect the requirements of modern high-gain VRs. Detailed discussions of the rest design can be found in [11]. Fig.3 shows responses of terminal voltage to step in 0.1 pu V_{ref}, open loop and closed loop for K_p=10, 20,…50.

From [11], transfer function of CPSS is

$$\frac{num(s)}{den(s)} = \frac{221.48[s^2 + 5.88s + 8.6436]}{s^2 + 69.8s + 1218.01}.$$

Detailed discussions of PSS design technique based on the synchronizing and damping torque concept can be found in many references such as [1], [4]. In the PSS projects these ideas were translated into procedures that could be followed by students with basic control system design skills.

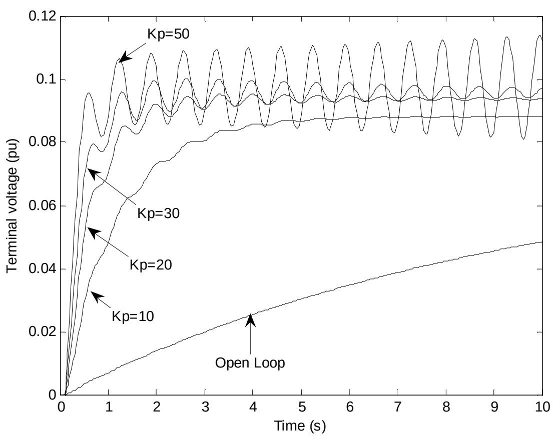

Fig.3. V_{term} responses to step in 0.1 pu V_{ref}, open loop and closed loop for K_p=10, 20,…50.

3. FUZZY LOGIC CONTROLLER (FLC)

Fuzzy logic controllers are rule-based controllers [10]. The structure of the FLC resembles that of a *knowledge-based* controller except that FLC utilizes the principles of fuzzy set theory in its data representation and its logic. The basic configuration of the FLC can be simply represented in four parts, as shown in Fig. 5.

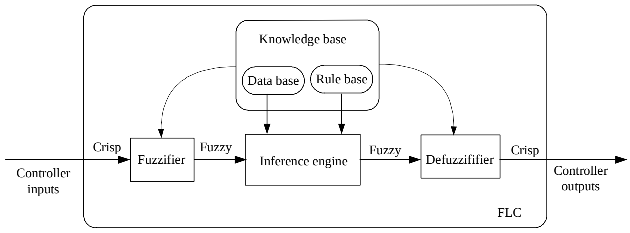

Fig. 5. Schematic diagram of the FLC building blocks

- *Fuzzification module*, the function of which are, first, to read, measure, and scale the control variable (e.g. speed, acceleration) and, second, to transform the measured numerical values to the corresponding linguistic (fuzzy) variables with appropriate membership values.
- *Knowledge base*, which includes the definitions of the fuzzy membership functions defined for each control variables and the necessary rules that specify the control goals using linguistic variables.
- *Inference mechanism*, which is the kernel of the FLC. It should be capable of simulating human decision making and influencing the control actions based on fuzzy logic.
- *Defuzzification module*, which converts the inferred decision from the linguistic variables back to numerical values.

Justification of Fuzzy Control Rules

There are two principal approaches to the derivation of fuzzy control rules [7]. The first is a heuristic method in which a collection of fuzzy control rules is formed by analying the behavior of a controlled process. The control rules are derived in such a way that the deviation from a desired state can be corrected and the control objective can be achieved. The derivation is purely heuristic in nature and relies on the qualitative knowledge of process behavior. The second approach is basically a deterministic method which can systematically determine the linguistic structure and/or parameters of the fuzzy control rules that satisfy the control objectives and constraints.

For example, Fig. 6 shows the system response of a process to be controlled, where the input variables of the FLC are the error (*E*) and error derivative (*DE*). The output is the change of the process input (*CI*). We assume that the term sets of input/output variables have the same cardinality, 3, with a common term {negative, zero, positive}. The prototype of fuzzy control rules is tabulated in Table 1 and a justification of fuzzy control rules is added in Table 2. The corresponding rule of region *i* can be formulated as rule R_i and has the effect of shortening the rise time. Rule R_{ii} for region *ii* decreases the overshoot of the system's response. More specifically:

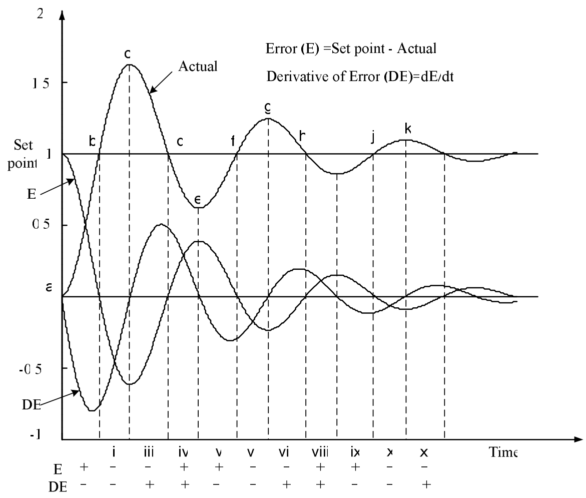

Fig.6. Rule justification by step response.

R_i: If (E is positive and DE is negative) Then CI is positive,

R_{ii}: If (E is negative and DE is negative) Then CI is negative.

Better control performance can be obtained by using finer fuzzy partitioned subspaces, for example, with the term set {NB: negative big, NM: negative medium, NS: negative small, ZE: zero, PS: positive small, PM: positive medium, PB: positive big}. The prototype and the justification of fuzzy control rules are also given in Table 3 and Table 4.

Table 1. Prototype of Fuzzy Control Rules with Term Sets {Negative, Zero, Positive}

Rule No.	*E*	*DE*	*CI*	Reference Point
1	*P*	*Z*	*P*	a, e, i
2	*Z*	*N*	*N*	b, f, j
3	*N*	*Z*	*N*	c, g, k
4	*Z*	*P*	*P*	d, h, l
5	*Z*	*Z*	*Z*	set point

Table 2. Rule Justification with Term Sets {Negative, Zero, Positive}

Rule No.	*E*	*DE*	*CI*	Reference Point
6	*P*	*N*	*P*	i (rise time), v
7	*N*	*N*	*N*	ii (overshoot), vi
8	*N*	*P*	*N*	iii, vii
9	*P*	*P*	*P*	iv, viii
10	*P*	*N*	*Z*	ix
11	*N*	*P*	*Z*	xi

Table 3. Prototype of Fuzzy Control Rules with Term Sets {*NB, NM, NS, ZE, PS, PM, PB*}

Rule No.	*E*	*DE*	*CI*	Reference Point
1	*PB*	*ZE*	*PB*	a
2	*PM*	*ZE*	*PM*	e
3	*PS*	*ZE*	*PS*	i
4	*ZE*	*NB*	*NB*	b
5	*ZE*	*NM*	*NM*	f
6	*ZE*	*NS*	*NS*	j
7	*NB*	*ZE*	*NB*	c
8	*NM*	*ZE*	*NM*	g
9	*NS*	*ZE*	*NS*	k
10	*ZE*	*PB*	*PB*	d
11	*ZE*	*PM*	*PM*	h
12	*ZE*	*PS*	*PS*	l
13	*ZE*	*ZE*	*ZE*	set point

Table 4. Rule Justification with Term Sets {*NB, NM, NS, ZE, PS, PM, PB*}

Rule No.	*E*	*DE*	*CI*	Reference Point
14	*PB*	*NS*	*PM*	i (rise time)
15	*PS*	*NB*	*NM*	i (overshoot)
16	*NB*	*PS*	*NM*	iii
17	*NS*	*PB*	*PM*	iii
18	*PS*	*NS*	*ZE*	ix
19	*NS*	*PS*	*ZE*	xi

Design two input signals of FLC

In this paper, crisp input values used in FLC are active power deviation and its derivative. The membership function and range of two input signals shown in Fig. 7 and Fig. 8.

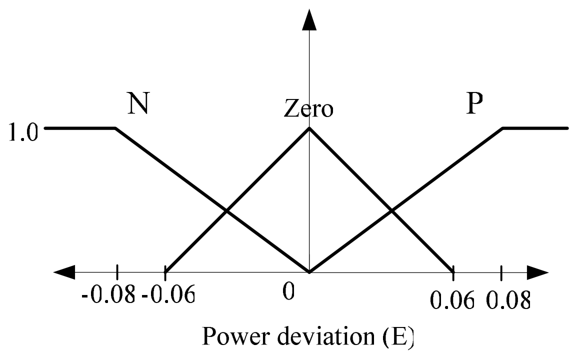

Fig.7. Three fuzzy sets of power deviation.

The membership function of stabilizing fuzzy set shows in Fig. 9.

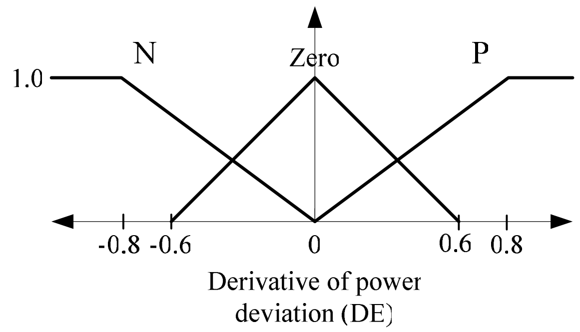

Fig.8. Three fuzzy sets of derivative of power deviation.

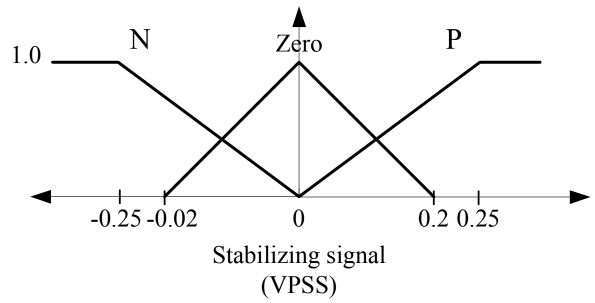

Fig.9. Three fuzzy sets of stabilizing signal (VPSS).

Table 5. Nine Fuzzy Control Rules for generate stabilizing signal

Power deviation (E) \ Derivative of power derivative (DE)	N	Z	P
N	N	N	N
Z	N	Z	P
P	P	P	P

The entries of matrix in Table 5 refer to the stabilizing signal as conditions of active power deviation and its derivative. Using Fuzzy Logic Toolbox [13] and Simulink drawing diagram show in Fig. 10. The parameters of FLPSS structure is choose fuzzy *mamdani* type, AndMethod using 'min', OrMethod using 'max', ImpMethod using 'min', AggMethod using 'max', and DefuzzMethod using 'centroid'.

4. SIMULATION RESULTS

Figure 11 shows a schematic diagram of the test system with CPSS and FLPSS. In order to trigger weak mode or oscillation, the system was perturbed with 0.1 p.u step change in reference voltage.

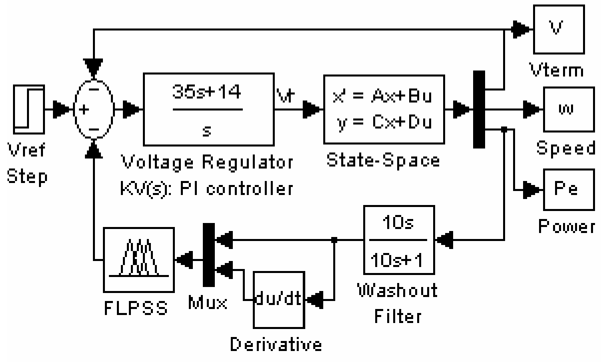

Fig.10. State space model of power system with FLPSS.

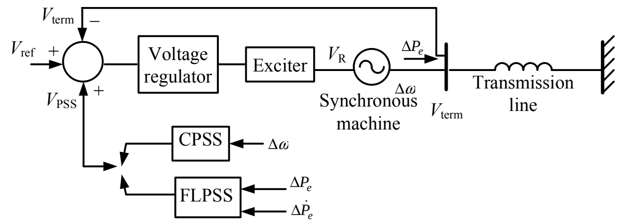

Fig.11. Single-machine infinite-bus system with CPSS and FLPSS.

Figure 12 shows power deviations of generator for all three cases, namely with PSS, with conventional PSS (CPSS) and Fuzzy Logic based PSS (FLPSS). As can be clearly seen from the response, the system without PSS is leading to oscillation with frequency around 1.5Hz and it takes more than 10 seconds for damping oscillation. With CPSS the oscillation triggered by step change is reference voltage is damped within 4 seconds. However, when FLPSS is introduced in the system, though the time taken for damping oscillation is the same the CPSS case, the amplitude of oscillation is lower. It should be noted that here FLPSS performance can be improved further by applying different membership function and also by considering better control input signals as FLPSS can accommodate many control input signals.

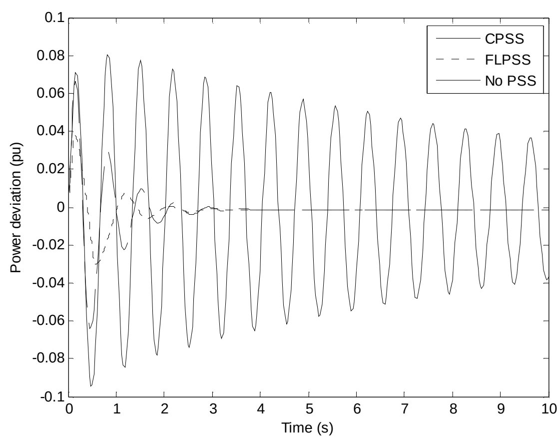

Fig.12. Active power deviation responses to step in 0.1 pu V_{ref}.

Similar pattern of responses can be observed in rotor speed deviation and excitation voltage as shown in Figs. 13 and 14, respectively.

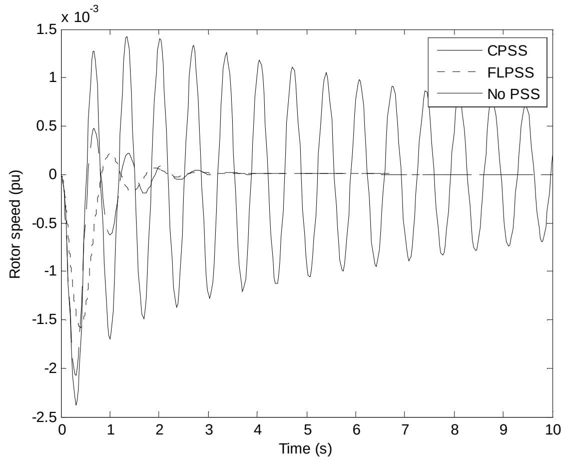

Fig. 13. Rotor speed deviation responses to step in 0.1 pu V_{ref}.

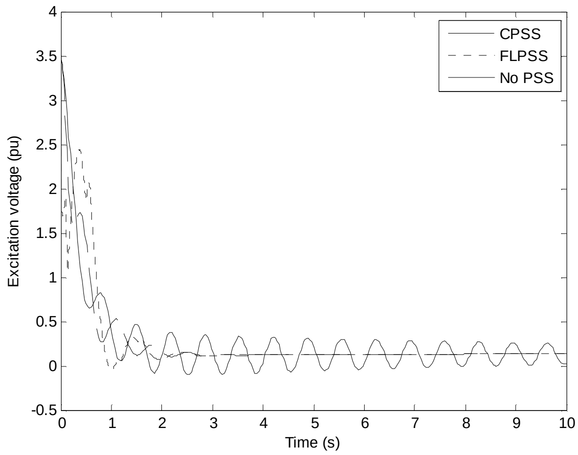

Fig.14. Excitation voltage responses to step in 0.1 pu V_{ref}.

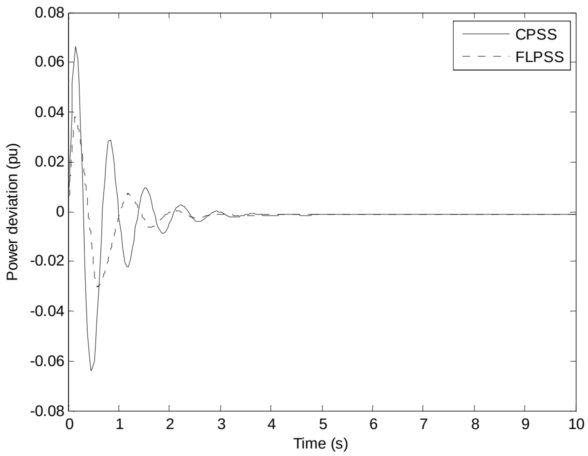

Fig.15. Active power deviation responses to step in 0.1 pu V_{ref}.

Figures 15 to 17 compare performances of CPSS and FLPSS. The time taken for damping and amplitude of oscillation are clear. As can be seen from figures the time taken for damping oscillation is slightly better in the case of FLPSS and the amplitude of oscillation is about 50% less than the case with CPSS. It should be noted here that power deviation and its derivative are used as control input signals.

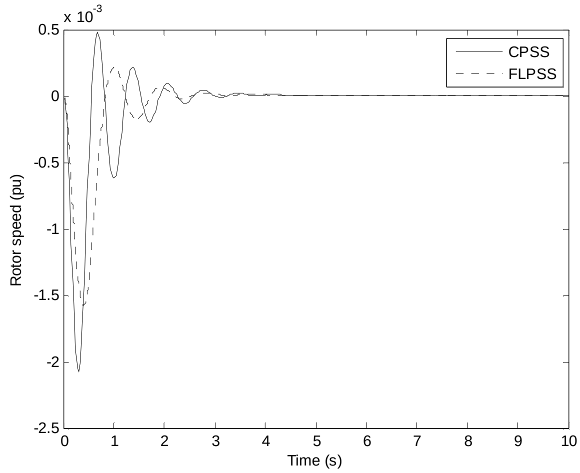

Fig.16. Rotor speed deviation responses to step in 0.1 pu V_{ref}.

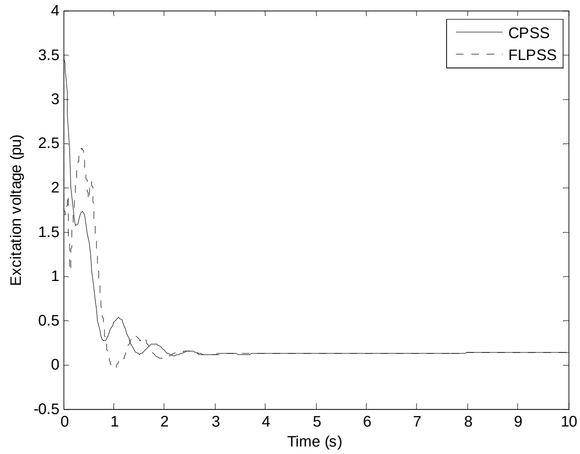

Fig.17. Excitation voltage responses to step in 0.1 pu V_{ref}.

5. CONCLUSION

The paper presents fuzzy logic-based PSS design for oscillation damping. It systematically explains the steps involved in fuzzy logic control design for oscillation damping in power system.

A comparison between the FLPSS and the CPSS shows that the FLPSS provides better performance than CPSS. The results show that the proposed FLPSS provides good damping and improves the dynamics.

Unlike the classical design approach which requires a deep understanding of the system, exact mathematical models, and precise numerical values, a basic feature of the fuzzy logic controller is that a process can be controlled without the knowledge of its underlying dynamics. The control strategy learned through experience can be expressed by set of rules that describe the behavior of the controller using linguistic terms. Proper control action can be inferred from this rule base that emulates the role of the human operator or a benchmark control action. Thus, fuzzy logic controllers are suitable for nonlinear, dynamic processes for which an exact mathematical model may not be available.

Using the principles of fuzzy logic control, a PSS has been designed to enhance the operation and stability of a power system. Results of simulation studies look promising.

REFERENCES

[1] Larsen, E.V. and Swann, D.A. 1981. Applying Power System Stabilizers Part I-III. *IEEE Trans. on Power Apparatus and Systems* PAS-100(6), pp. 3017-3046.

[2] Kundur, P. 1994. *Power System Stability and Control*. New York: McGraw-Hill.

[3] Machowski, Jan.; Bialek, J.W.; and Bumby, J.R. 1997. *Power System Dynamics and Stability*. Singapore: John Wiley & Sons.

[4] Murdoch, A.; Venkataraman, S.; Lawson, R.A.; and Pearson, W.R. 1999. Integral of Accelerating Power Type PSS Part 1 – Theory, Design, and Tuning Methodology. *IEEE Trans. On Energy Conversion*. 14(4), pp. 1658-1663.

[5] Rogers, G. 2000. *Power System Oscillations*. London: Kluwer Academic Publishers.

[6] Pal, B.; and Chaudhuri, B. 2005. *Robust Control in Power Systems*. New York, Springer Science + Business Media.

[7] Lee, C.C. 1990. Fuzzy Logic in Control Systems: Fuzzy Logic Controller-Part I. *IEEE Trans. on systems, man, and cybernetics* 20(2), pp. 404-418.

[8] Hsu, Y.Y; and Cheng, C.H. 1990. Design of Fuzzy Power System Stabilizers for Multimachine Power Systems. *IEE Proceedings, 137(3), Pt. C,* pp. 233-238

[9] EI-Metwally, K.A.; and Malik, O.P. 1995. Fuzzy Logic Power System Stabiliser. *IEE Proc.-Gener. Transm. Distrib*. 142(3), pp. 277-281.

[10] Malik, O.P.; and El-Metwally, K.A.M. 1998. Fuzzy Logic Controller as a Power System Stabilizer. *Electric Power Application of Fuzzy Systems*. IEEE Press.

[11] Chow, J.H.; Boukarim, G.E.; and Murdoch, A. 2004. M Power System Stabilizers as Undergraduate Control Design Projects. *IEEE Trans. on Power Systems* 19(1), pp. 144-151.

[12] Frederrick, D.K. and Chow, J.H. 2000. *Feedback Control Problems using MATLAB and the Control System Toolbox*. Calif.: Brooks/Cole Publishing Company.

[13] The MathWorks. 2007. *Fuzzy Logic Toolbox 2 User's Guide*. MATLAB, Online only, http:/www.mathworks.com.

APPENDIX

APPENDIX A: STATE-SPACE MODEL.

Parameters of matrix A, B, C and D are used in the test system as following.

$$A=[\begin{array}{ccccccc} 0 & 377.0 & 0 & 0 & 0 & 0 & 0; \\ -0.246 & -0.156 & -0.137 & -0.123 & -0.0124 & -0.0546 & 0\,; \\ 0.109 & 0.262 & -2.17 & 2.30 & -0.0171 & -0.0753 & 1.27; \\ -4.58 & 0 & 30.0 & -34.3 & 0 & 0 & 0; \\ -0.161 & 0 & 0 & 0 & -8.44 & 6.33 & 0; \\ -1.70 & 0 & 0 & 0 & 15.2 & -21.5 & 0; \\ -33.9 & -23.1 & 6.86 & -59.5 & 1.50 & 6.63 & -114 \end{array}]$$

B=[0; 0; 0; 0; 0; 0; 16.4]

$$C=[\begin{array}{ccccccc} -0.123 & 1.05 & 0.230 & 0.207 & -0.105 & -0.460 & 0; \\ 0 & 1 & 0 & 0 & 0 & 0 & 0; \\ 1.42 & 0.900 & 0.787 & 0.708 & 0.0713 & 0.314 & 0 \end{array}]$$

D = [0; 0; 0]