Design of Augmented Fuzzy Logic Power System Stabilizers to Enhance Power Systems Stability

Hamid A. Toliyat
Member, IEEE
Department of Electrical Engineering
Texas A&M University
College Station, TX 77843-3128
Fax: (409) 845-6259

Javad Sadeh
Non Member

Reza Ghazi
Member, IEEE
Department of Electrical Engineering
Ferdowsi University of Mashhad
Mashhad, Iran
Fax : +98-51-836433

Abstract - This paper presents an augmented fuzzy logic power system stabilizer (PSS) for stability enhancement of multimachine power systems. In order to accomplish a satisfactory damping characteristic over a wide range of operating points, speed deviation ($\Delta\omega$) and acceleration ($\Delta\dot{\omega}$) of a synchronous generator were taken as the input signals to the fuzzy controller. It is well known that these variables have significant effects on damping the generators shaft mechanical oscillations. A modification of the terminal voltage feedback signal to the excitation system as a function of the accelerating power on the unit, is also used to enhance the stability of the system. The stabilizing signals are computed using the standard fuzzy membership function depending on these variables. The performance of the proposed augmented fuzzy controller is compared to an optimal controller and its effectiveness is demonstrated by a detailed digital computer simulation of a single machine infinite bus and a multimachine power systems.

Keywords: Fuzzy logic control, improved power system stabilizer, power system stability.

I. INTRODUCTION

In the past decades power system stabilizers have been widely used to provide the desired system performance under the condition that requires stabilization. Stability of synchronous generators is influenced by a number of factors such as the setting of the generator's automatic voltage regulator (AVR). Many generators are equipped with high gain, fast acting AVR's to enhance large scale stability by holding the generator in synchronism with the power system during large transient fault conditions. However, these high gain excitation systems can decrease the damping torque of the generators, leading to a system vulnerable to oscillatory instability.

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Weak transmission lines between generators and loads, operation of generators at wide power angles as a result of heavy loading, and particular load characteristic contribute to this oscillatory instability. A solution to this problem, would be building more transmission lines or adding generating capacity which are costly or impractical due to environmental or other constraints. For the past two decades supplementary excitation controllers referred to as power system stabilizers have been added to synchronous generators to counteract the effect of high gain AVR's and other sources of negative damping. To provide damping, the stabilizer must produce a component of electrical torque on the rotor which is in phase with speed variations [1]. The PSS feedback loop provides an economical way of enhancing the stability of a power system. The parameters setting of conventional stabilizers are determined off-line based on a particular operating condition to result in optimal performance for that specific condition. However, they might exhibit poor performance under different synchronous generator loading conditions.

Limitations of fixed parameters PSS's has lead to advanced control schemes, such as, self tuning control [2], sliding mode control [3], rule based PSS [4] and fuzzy logic control [5,6]. Although, all these controllers are capable of offering better dynamic performance than a fixed parameters PSS, the fuzzy logic control appears to be the most promising, due to its lower computational burden and robustness. Also, in the design of fuzzy logic controllers, unlike most conventional methods, a mathematical model is not required to describe the system under study.

The objective of this paper is to introduce an augmented fuzzy logic PSS to enhance the stability of power systems. The improved stabilizer utilizes the fuzzy logic PSS in the usual manner, plus modification of the terminal voltage feedback signal to the excitation system as a function of the accelerating power on the unit. The nonlinear action of the augmented fuzzy logic PSS increases the power system stability greatly, while it is simple to implement. The effectiveness of the proposed improved fuzzy PSS in a single machine infinite bus as well as a multimachine power system environment is demonstrated by a detailed digital computer simulation. Also, its performance is compared to an optimal controller. It is shown that by application of augmented fuzzy PSS to the power systems good dynamic performance over a wide range of operating conditions can be obtained.

II. INTRODUCTION TO FUZZY SET THEORY

First, a few definitions and mathematical operations of fuzzy sets are given [7]:

1) Definition of a fuzzy set:

Let X be a collection of objects, then a fuzzy set A in X is defined to be a set of ordered pairs:

$$A = \{ (x, \mu_A(x)) \mid x \in X \} \tag{1}$$

where $\mu_A(x)$ is called the membership function of x in A. The numerical interval X which is relevant for the description of a fuzzy variable, is commonly named Universe of Discourse. The membership function $\mu_A(x)$ denotes the degree to which x belongs to A and is normally limited to values between 0 and 1. A value of $\mu_A(x)$ close to one means it is very likely for x to be in A and a value of $\mu_A(x)$ nearer to zero denotes non membership. In case that the values of membership function are limited to be either zero or one, then A becomes a crisp or nonfuzzy set.

2) Fuzzy set operation:

It is well known that the membership functions play an important role in fuzzy sets. Therefore, it is not surprising to define the fuzzy set operators based on their corresponding membership functions. Operations like AND, OR, and NOT are some of the most important operators of the fuzzy sets.

Suppose A and B are two fuzzy sets with membership functions $\mu_A(x)$ and $\mu_B(x)$ respectively then,

a. *The AND operator or the intersection of two fuzzy sets*:

The membership function of the intersection of these two fuzzy sets ($C = A \cap B$), is defined by

$$\mu_C(x) = \min \{ \mu_A(x) \;,\; \mu_B(x)\} \;,\; x \in X \tag{2}$$

b. *The OR operator or the union of two fuzzy sets*:

The membership function of the union of these two fuzzy sets ($D = A \cup B$), is defined by

$$\mu_D(x) = \max \{ \mu_A(x) \;,\; \mu_B(x)\} \;,\; x \in X \tag{3}$$

c. *The NOT operator or the complement of a fuzzy set:*

The membership function of the complement of A, A', is defined by:

$$\mu'_A(x) = 1 - \mu_A(x) \qquad , \qquad x \in X \tag{4}$$

d. *Fuzzy relation*

A fuzzy relation R from A to B can be considered as a fuzzy graph and characterized by the membership function $\mu_R(x,y)$, which satisfies the composition rule as follows:

$$\mu_B(y) = \max_{x \in X} \left\{ \min\left[\mu_R(x,y) \,,\, \mu_A(x) \right] \right\} \tag{5}$$

III. FUZZY LOGIC CONTROLLER

Fuzzy control systems are rule-based systems in which a set of so-called fuzzy rules represent a control decision mechanism to adjust the effects of certain system stimuli. The aim of fuzzy control systems is normally to replace a skilled human operator with a fuzzy rule-based system. The fuzzy logic controller provides an algorithm which can convert the linguistic control strategy based on expert knowledge into an automatic control strategy. Figure 1 illustrates the basic configuration of a fuzzy logic controller which consists of a fuzzification interface, a knowledge base, a decision making logic, and a defuzzification interface.

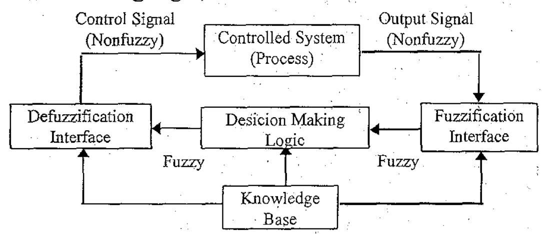


Figure 1 The principle design of a fuzzy logic controller.

IV. FUZZY LOGIC POWER SYSTEM STABILIZER

The first step in designing a fuzzy controller is to decide which state variables representative of system dynamic performance must be taken as the input signals to the controller. Moreover, choosing the proper linguistic variables formulating the fuzzy control rules are also important factors in the performance of the fuzzy control system. Empirical knowledge and engineering intuition play an important role in choosing linguistic variables and their corresponding membership functions. System variables, which are usually used as the fuzzy controller inputs include: states, states error, states error derivative, states error integral, etc. In power systems, based on previous experience, generator speed deviation ($\Delta\omega$) and acceleration ($\Delta\dot{\omega}$) are chosen to be the input signals of the fuzzy PSS. As it was mentioned previously, if the synchronous generator automatic voltage regulator is utilized in a proper way it is capable of damping electromechanical oscillations of the generator shaft. Therefore, the input to the excitation system would be the control variable which is actually the output of fuzzy PSS. In practice, only shaft speed deviation is readily available. Hence, the acceleration signal can be derived from the speed signals measured at two successive sampling instants:

$$\Delta\dot{\omega}(kT_s) = \frac{\Delta\omega(kT_s) - \Delta\omega[(k-1)T_s]}{T_s} \tag{6}$$

where T_s is the sampling time. After choosing proper variables as input and output of fuzzy controller, it is required to decide on the linguistic variables. These variables transform the numerical values of the input of the fuzzy controller, to fuzzy quantities. The number of these linguistic variables specifies the quality of the control which can be achieved using the fuzzy controller. As the number of the linguistic variables increases, the computational time and required memory increase. Therefore, a compromise between the quality of control and computational time is needed to choose the number of linguistic variables. Basically, the sensitivity of a variable determines the number of fuzzy subsets. For the power system under study, seven linguistic variables for each of the input and output variables are used to describe them. These are, LP (large positive), MP (medium positive), SP (small positive), VS (very small), SN (small negative), MN (medium negative), and LN (large negative).

In order to find the minimum and maximum of stabilizer inputs, an open loop simulation for different initial conditions is performed. The results are used to find the minimum and maximum of the ($\Delta\omega$) and ($\Delta\dot{\omega}$). After specifying the fuzzy sets, it is required to determine the membership functions for these sets. Functional definition, which express the membership function of a fuzzy set in a functional form, typically a bell-shaped function, triangle-shaped function, trapezoidal-shaped function, etc. is used to define the membership functions. The degree of membership can be defined as functions when the control variables amplitude are continuous. In this paper, the triangular membership functions are used to define the degree of membership. It is important to note that the degree of membership plays an important role in designing a fuzzy controller. A set of rules which define the relation between the input and output of fuzzy controller can be found using the available knowledge in the area of designing PSS. These rules are defined using the linguistic variables. The two inputs, speed and acceleration, result in 49 rules for each machine. A proper way to show these rules is given in Table 2 [8] where all the symbols are defined in the basic fuzzy logic terminology. A typical rule has the following structure:

Rule 1: If speed deviation is LP (large positive) AND acceleration is LN (large negative) then Vpss (output of fuzzy PSS) is VS (very small). (7)

Table 1 Decision table for PSS output.

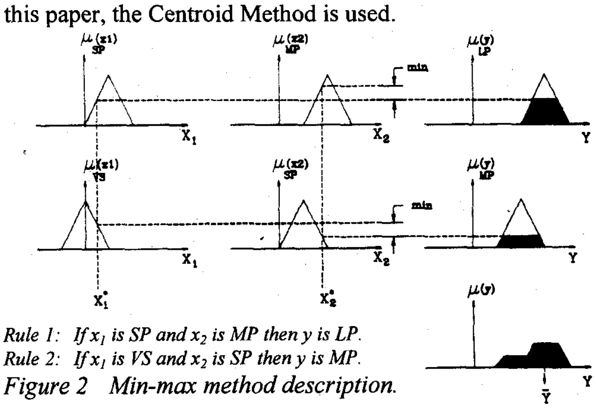
($\Delta\dot{\omega}$) / ($\Delta\omega$)	PSS output LN	MN	SN	VS	SP	MP	LP
LP	VS	SP	MP	LP	LP	LP	LP
MP	SN	VS	SP	MP	MP	LP	LP
SP	MN	SN	VS	SP	SP	MP	LP
VS	MN	MN	SN	VS	SP	MP	MP
SN	LN	MN	SN	SN	VS	SP	MP
MN	LN	LN	MN	MN	SN	VS	SP
LN	LN	LN	LN	LN	MN	SN	VS

It is clear that each entry in Table 1 represents a particular rule. The above decision table can be transformed into the fuzzy relation matrix of Table 2 [13]. The stabilizer output is obtained by applying a particular rule expressed in the form of membership functions. For example the first line of Table 2 [13] is as follows:

If ($\Delta\omega$) is LP and ($\Delta\omega$) is LN, then the stabilizer output V_{PSS} can be given by the fuzzy set {(LN, 0), (MN, 0), (SN, 0.5), (VS, 1), (SP, 0.5), (MP, 0), (LP, 0)}.

Now it is required to find the fuzzy region for the output for each fuzzy rule. There are different methods for finding the output, which Minimum-Maximum and Maximum-Product methods [9] are among the most important ones. In this paper, the Min-Max method is used.

Fuzzy rules are connected using AND operators and it was defined previously that AND operator means finding minimum between two membership functions. The AND operator is used to obtain the minimum between input membership functions. Later, the minimum between this result and the output membership function is found. Finally, the output membership function of a rule is calculated. This procedure, is carried out for all of the rules and for every rule an output membership function is obtained. To find the output membership function due to all of these rules, the maximum among all of these rules is calculated. This method is specifically presented in Figure 2. Since a nonfuzzy signal is needed for the excitation system, by knowing the membership function of the fuzzy controller its numerical value should be determined. There are different techniques for defuzzification of fuzzy quantities such as Maximum Method, Height Method, and Centroid Method. In this paper, the Centroid Method is used.



Rule 1: If x_1 is SP and x_2 is MP then y is LP.
Rule 2: If x_1 is VS and x_2 is SP then y is MP.
Figure 2 Min-max method description.

In this defuzzification method, the weighted average of the membership function or the center of gravity of the area bounded by the membership function curve is computed to be the most typical crisp value of the fuzzy quantity, i.e.:

$$\bar{y} = \frac{\int y\mu(y)dy}{\int \mu(y)dy} \quad (8)$$

This defuzzification method, is depicted in Figure 2.

V. SINGLE MACHINE INFINITE BUS SYSTEM

The system studied is a single machine infinite bus power system as presented in Figure 3. The synchronous machine is equipped with IEEE type DC1A exciter [10]. Governor effects are included in the simulation. In the simulation studies, the synchronous machine is represented by a 7th order model, the exciter and governor-turbine are represented by a 4th order model and a 2nd order model, respectively [11]. The system equations linearized around the operating point, were developed in the state space form using the component connection method [12]. The overall system has 13 states. The pertinent parameters are given in the appendix. Figure 4 (a) shows the simulation results for a period of 5 seconds following 5% increase in mechanical power step change (ΔP_c). It is clear that the system response even after 5 seconds is still oscillatory and a PSS is required to damp the system oscillations. In this paper three different types of controllers namely conventional PSS, optimal feedback controller, and fuzzy PSS are considered and the performance of these controllers are compared against augmented fuzzy PSS.

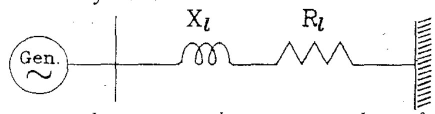
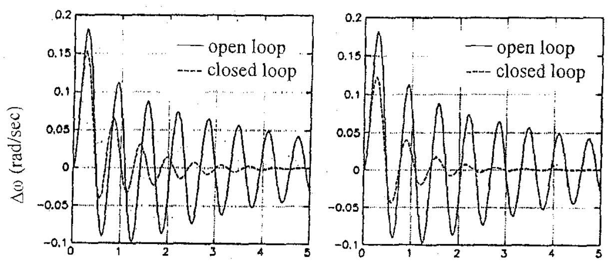


Figure 3 Synchronous machine connected to infinite bus.



(a) Time (sec.) (b) Time(sec.)

Figure 4 The system speed response for 5% increase in Δp_C. a)Conventional PSS. b) optimal feedback regulator

a) Conventional PSS:

The synchronous generator is equipped with a conventional PSS with the following transfer function [1]:

$$G(s) = K_s\left(\frac{1+T_1 s}{1+T_2 s}\right)\left(\frac{1+T_3 s}{1+T_4 s}\right) \tag{9}$$

Figure 4(a) presents the simulation results for a 5% increase in (Δp_c) with a conventional PSS. It is clear that the system response is damped.

b) Optimal feedback controller

The synchronous generator is equipped with a linear quadratic regulator. An objective function based on the state variables and inputs is defined. In this study, the weighting matrices are unit matrices with proper dimensions. Figure 4(b) illustrates the simulation results for a 5% increase in (ΔP_c). It is clear that the settling time is substantially reduced.

c) Fuzzy PSS

In this case, the synchronous generator is equipped with a fuzzy PSS [13]. Figure 5 illustrates the membership functions of input variables of the fuzzy PSS. Suppose that at a particular sampling instant, the sampled stabilizer inputs are

$$\Delta\omega = 0.018 \text{rad/sec} \qquad \Delta\dot{\omega} = -0.0004 \text{p.u.}$$

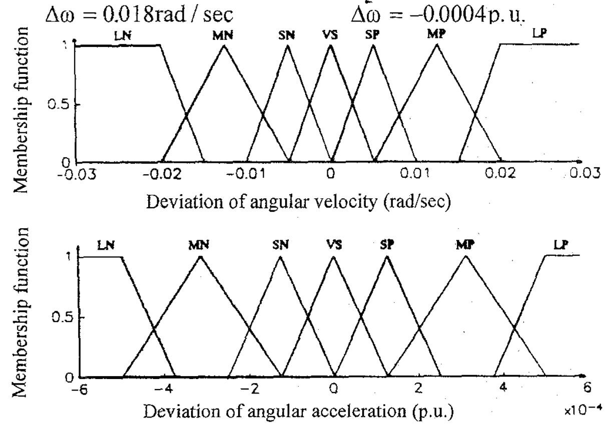


Figure 5 Membership functions, a) speed deviation, b) acceleration.

The two stabilizer inputs with respect to Figure 5 would be described by the following fuzzy sets:

$$\{\Delta\omega\} = \{(LN, 0), (MN, 0), (SN, 0), (VS, 0), (SP, 0), (MP, .267), (LP, .6)\}$$
$$\{\Delta\dot{\omega}\} = \{(LN, .2), (MN, .533), (SN, 0), (VS, 0), (SP, 0), (MP, 0), (LP, 0)\} \tag{10}$$

To find the membership function of the stabilizer output using Table 2 presented in [13], it is required to find the membership value for the condition part of each rule. For example for Rule 1:

$$\mu(x_1) = \mu(\Delta\omega \text{ is LP and } \Delta\dot{\omega} \text{ is LN}) = \min[\mu(\Delta\omega \text{ is LP}), \mu(\Delta\dot{\omega} \text{ is LN})] = \min[0.6, 0.2] = 0.2 \tag{11}$$

Using equation (5), the membership values for the stabilizer output characterized by the seven linguistic variables LN, MN, SN, VS, SP, MP, LP can be obtained. For example:

$$\mu_{V_{pss,1}}(LN) = \min[\mu_R(x_1, LN), \mu(x_1)] = \min[0, 0.2] = 0 \tag{12}$$

This is the membership value of the stabilizer output 'LN' if only Rule 1 exists. In order to take all the 49 rules into account, the membership values for the condition part of all the other 48 rules must be considered. The final value for stabilizer output 'LN' can be evaluated using equation (5):

$$\mu_{V_{pss}}(LN) = \max_{x_i}\{\min[\mu_R(x_i, LN), \mu(x_i)]\} \tag{13}$$

The membership values for the other six variables can be similarly calculated as:

$$\mu_{V_{Pss}}(LN) = 0 \quad \mu_{V_{Pss}}(MN) = 0.2 \quad \mu_{V_{Pss}}(SN) = 0.267$$
$$\mu_{V_{Pss}}(VS) = 0.5 \quad \mu_{V_{Pss}}(SP) = 0.533 \quad \mu_{V_{Pss}}(MP) = 0.5$$

$$\mu_{V_{Pss}}(LP) = 0 \quad (14)$$

A proper algorithm is required to determine the stabilizer output signal. The technique adopted in this paper, is the Centroid Method given by equation (8) and repeated here for convenience:

$$\overline{V}_{Pss} = \frac{\sum_{i=1}^{7} \mu_{V_{Pss}}(A_i) V_{Pss,i}}{\sum_{i=1}^{7} \mu_{V_{Pss}}(A_i)} \quad (15)$$

where A_i represents the linguistic variables and $V_{Pss,i}$ is the numerical value of V_{Pss} for the given A_i. These values can be obtained using Table 2 which are based on pervious experience with power system stabilizers. As a result V_{Pss} will be given by:

$$V_{Pss}=[0.(-.1)+.2(-.04)+.267(-.02)+.5(0)+.533(.02)+.5(.04)+0.(.1)] / (0+.2+.267+.5+.533+.5+0) = 0.00866$$

Table 2 Conversion table from linguistic variables to numerical values.

	LN	MN	SN	VS	SP	MP	LP
V_{PSS}	-0.1	-.04	-.02	.0	.02	.04	.1

Figures 6(a) presents the system responses to a 5% increase in ΔP_C. It is obvious that the system response with the fuzzy PSS is better than the case of conventional PSS and is comparable to the optimal feedback controller. However, it is important to note that in the case of optimal feedback controller, all states should be available which is a rather difficult task in the majority of physical systems. On the other hand, for fuzzy controller only shaft speed information (which is readily available) is required.

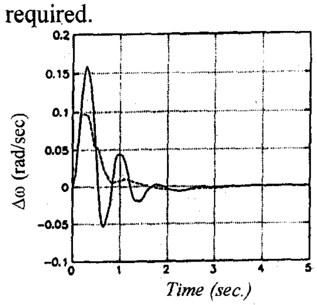


Figure 6 The system speed response for 5% increase in Δp_C.
a) Fuzzy PSS ———
b) Augmented fuzzy PSS -------

d) Augmented Fuzzy PSS

A proper stabilizing signal derived from the machine terminal voltage and introduced into the excitation system can increase the damping torque of the synchronous machine and consequently improve the performance of the conventional PSS [14]. In the proposed augmented fuzzy PSS, an auxiliary stabilizing signal, ΔP_a, which is a function of accelerating power into the terminal voltage feedback loop is utilized. This accelerating power is the difference between mechanical power and electrical power. In designing the fuzzy PSS, synchronous machine acceleration should be calculated in every step. In the case of augmented fuzzy PSS, there is no need for an extra computational effort. Figure 7 is the block diagram of the augmented fuzzy stabilizer, where the feedback from terminal voltage V_t is a function of ΔP_a.

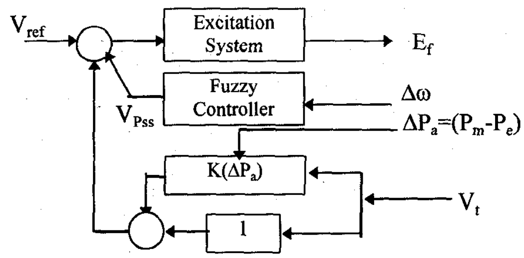
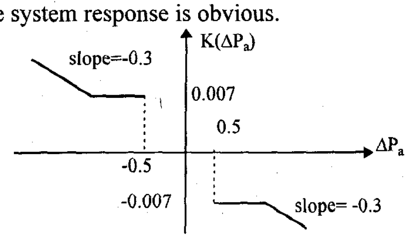


Figure 7 Block diagram of improved fuzzy stabilizer.

The terminal voltage feedback is a nonlinear feedback due to the fact that K is a function of ΔP_a. The basics of designing K is as follows:

When ΔP_a is greater than zero, the mechanical power is larger than the electrical power, thus, negative gain (K) should be chosen to increase the terminal voltage. This higher terminal voltage will immediately boost the electrical power to balance the mechanical power. If ΔP_a is less than zero, a positive gain will be selected. Figure 8 illustrates K as a function of accelerating power. Figure 6 (b) shows the system response to a 5% increase in ΔP_C. It is shown that this representation for augmented PSS is effective for reducing the overshoot and the settling time. A marked improvement in the system response is obvious.

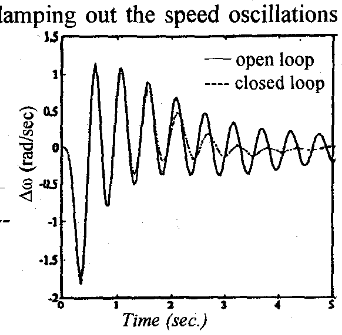
Figure 8 Gain for the improved fuzzy stabilizer.



e) Three Phase Fault at the Machine Terminal

In order to validate the overall effectiveness of the proposed augmented fuzzy PSS, the full order nonlinear model of the system was simulated. A 0.2 sec. three phase to ground fault at generator terminal was simulated. Figure 9 illustrates the variation of the angular speed deviation after the fault was cleared. The successful performance of the augmented fuzzy PSS in damping out the speed oscillations is obvious.

Figure 9 The system speed response after the three phase fault.
a) Open loop ——
b) Augmented fuzzy PSS ----



VI. Multimachine System

The three machine infinite bus equivalent power system shown in Figure 10 is used for the multimachine study. The three synchronous generators are fossil, nuclear, and hydro units respectively. The first two machines are equipped with static exciters and the third machine has an IEEE type DC1A exciter. All the three machine models include the governor model. The data for three machines are given in the appendix. Each synchronous generator is represented by a 7th order model. Figure 11 shows the simulation results for a period of 6 seconds following 5% increase in mechanical power step change (ΔP_c) of machine 1. An oscillatory response even after 6 seconds specially in machine 2 and 3 due to small negative mechanical modes eigenvalues, is obvious. The system response after application of centralized optimal state feedback regulator is shown in Figure 11. It is clear that the system response is substantially improved. However, a complex centralized optimal regulator which requires all the states to be dispatched to the central controller is needed.

In the next study each synchronous generator is equipped with an augmented fuzzy controller. Figure 5 presents the membership functions of input variables of the fuzzy PSS which are the speed and acceleration of each machine. Figure 11 shows the system speed response to 5% increase in Δp_{c1}. Clearly the performance of the system is comparable to that of the optimal state feedback regulator.

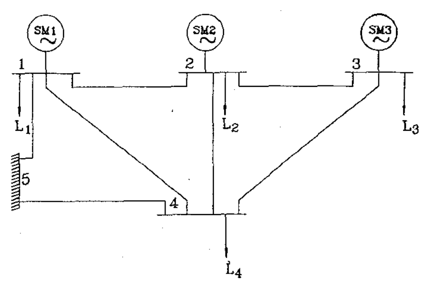


Figure 10 Three generators, infinite bus system.

VII. Conclusions

In this paper, an augmented fuzzy power system stabilizer is introduced. Speed deviation ($\Delta\omega$) and acceleration ($\Delta\dot{\omega}$) of synchronous generator were taken as the input signals to the fuzzy controllers. To further increase the stability of the power system, a modification of the terminal voltage feedback signal to the excitation system as a function of the accelerating power on the machine is utilized. It is shown that the augmented fuzzy PSS is capable of further enhancing the power system dynamics. The controller performance is comparable to that of the optimal regulator. The effectiveness of the proposed method has also been shown using the large signal nonlinear response of the system under three phase short circuit. The proposed controller has been applied to a multimachine power system. The system response has been compared with respect to the centralized optimal state feedback regulator and it is shown that similar performance can be obtained from augmented fuzzy PSS. A comprehensive digital computer simulation which includes the detailed models of power system components were used to prove the effectiveness of the proposed augmented fuzzy PSS.

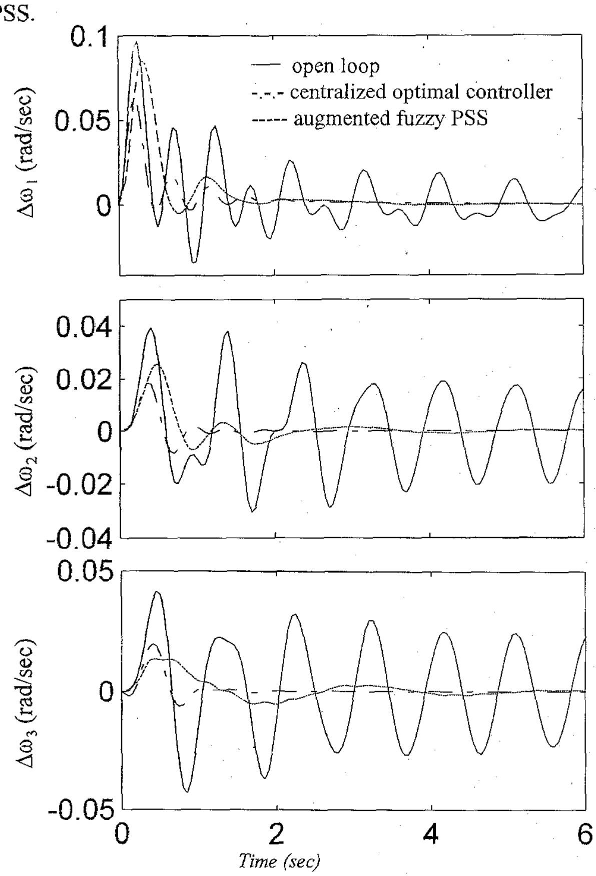


Figure 11 a) The system speed ($\Delta\omega$) variations for 5% increase in Δp_{c1}. a) Centralized optimal state feedback regulators, b) Augmented fuzzy PSS on all machines.

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IX. APPENDIX

Parameters For The Single Machine Infinite Bus Study

Synchronous generator parameters (p.u.):

$\omega_b = 377$ rad/sec.	$x_d = 1.7$ p.u.	$x_q = 1.64$ p.u.
$x_{fd} = 1.651$ p.u.	$x_{kd} = 1.605$ p.u.	$x_{kq} = 1.526$ p.u.
$x_\ell = .15$ p.u.	$r_a = .001096$ p.u.	$r_{fd} = .000742$ p.u.
$r_{kd} = .0131$ p.u.	$r_{kq} = .054$ p.u.	$H = 2.37$ sec. $D=0$.

IEEE Type DC1A exciter System

$K_R = 1$	$T_R = .01$	$K_A = 40$
$T_A = .05$	$K_E = -.05$	$T_E = .5$
$S_E = .3095$	$K_F = .04$	$T_F = .715$

Turbine-Governor System

$K_g = 20$	$T_g = .01$	$T_t = .3$

Transmission line

$R_e = .02$ p.u.	$X_e = .4$ p.u.

Operating points

$P = 1$ p.u.	$Q = .62$ p.u.	$V = 1.0$ p.u.

Conventional power system stabilizer

$K_s = 14.76$	$T_1 = T_3 = 0.1176$	$T_2 = T_4 = 0.05$

Optimal Feedback Controller Parameters

The optimal feedback controller parameters which were found by solving the Riccati's equations are as follows:

$$\begin{bmatrix} \Delta v_{ref} \\ \Delta p_c \end{bmatrix} = \begin{bmatrix} -.0881 & -.82047 & .08065 & .79882 & .85068 & .045376 & .21372 & -.86786 & -.93025 & .97722 & .81595 & -.001814 & .000081 \\ .21209 & 1.4121 & .22156 & -1.4245 & -1.4794 & -.86617 & 32.834 & .00002 & -.01391 & -.000008 & -.00243 & 1.4812 & -.04671 \end{bmatrix}$$

Parameters For The Multimachine Study

Synchronous Generators Parameters(p.u.)

	G1	G2	G3
r_a	.00165	.0014446	.001063
x_{aq}	1.1222	.8929	.12567
x_{ad}	1.2303	.8929	.21608
r_{kq}	.002735	.002391	.015244
x_{kq}	1.3676	.973228	.18788
r_{kd}	.008703	.007606	.007622
x_{kd}	1.3254	.973228	.2492
r_{fd}	.000809	.000369	.000133
x_{fd}	1.3147	.9643	.269417
X_ℓ	.171	.097	.04688
H	3.127	5.715	5.2685
D	0	0	0

Static Exciter System (fossil and nuclear units)

$K_{E1}=350$	$K_{E2}=200$
$T_{E1}=.002$	$T_{E2}=.002$

IEEE TypeDC1A Exciter System (hydro unit)

$K_R = 1$	$T_R = .03$	$K_A = 200$
$T_A = .05$	$K_E = -.17$	$T_E = .95$
$S_E = .95$	$K_F = .04$	$T_F = 1$

Turbine-Governor System

Fossil:	$K_g=20$	$T_g=.1$	$T_t=.3$
Nuclear:	$K_g=20$	$T_g=.4$	$T_t=.3$
Hydro:	$K_g=20$	$T_1=.4$	$T_2=.4$
	$T_5=.35$		

Transmission Lines Data:

Line	Resistance(p.u.)	Reactance(p.u.)
1-5	.06	.6
1-2	.05	.5
2-3	.06	.6
3-4	.05	.5
4-5	.02	.2
1-4	.03	.3
2-4	.03	.3

Electric Loads

L1:	.2+j.15	L2:	.3+j.25
L3:	.2+j.15	L4:	.6+j.5

Hamid A. Toliyat (S'87-M'91) was born in Mashhad, Iran, in 1957. He received the B.S. (1982) and M.S. (1986) in electrical engineering from Sharif University of Technology, Tehran, Iran and West Virginia University, Morgantown, WV, respectively. He received his Ph.D. degree in electrical engineering from the University of Wisconsin-Madison in 1991. In 1991 he joined the faculty of Ferdowsi University of Mashhad, Mashhad, Iran as an assistant professor of electrical engineering. He is currently an assistant professor at the Texas A&M University.

Dr. Toliyat is a member of the IEEE Power Engineering and Industry Application Societies. His main research interests and experience include variable speed drives, analysis and design of electric machines, power electronics, electric and hybrid vehicle traction systems, power systems and control.

Javad Sadeh was born in Mashhad, Iran, in 1968. He received his B.Sc. degree (with honors) from Ferdowsi University of Mashhad, Mashhad, Iran, in 1990 and M.Sc. degree from the same school in 1994. His research interests include power system stability.

Reza Ghazi (M'90) was born in Simnan, Iran, in 1952. He received his B.Sc. degree from Tehran University of Science & Technology in 1976. In 1986 he received his M.Sc degree from Manchester University, Institute of Science and Technology (UMIST), and the Ph.D. degree in 1989 from Salford University, UK, both in electrical engineering. Since 1989 he has been an assistant professor in electrical engineering department of Ferdowsi University of Mashhad, Mashhad, Iran. His research interests include reactive power control and static VAR compensators (SVC's).