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Fuzzy Applications in a Multi-Machine Power System Stabilizer

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Abstract - This paper proposes the use of fuzzy applications to a 4-machine and 10-bus system to check stability in open conditions. Fuzzy controllers and the excitation of a synchronous generator are added. Power system stabilizers (PSSs) are added to the excitation system to enhance damping during low frequency oscillations. A fuzzy logic power system stabilizer (PSS) for stability enhancement of a multi-machine power system is also presented. To attain stability enhancement, speed deviation $(\Delta\omega)$ and acceleration $(\Delta\varpi)$ of the Kota Thermal synchronous generator rotor are taken as inputs to the fuzzy logic controller. These variables have significant effects on the damping of generator shaft mechanical oscillations. The stabilizing signals are computed using fuzzy membership functions that are dependent on these variables. The performance of the fuzzy logic PSS is compared with the open power system, after which the simulations are tested under different operating conditions and changes in reference voltage. The simulation results are quite encouraging and satisfactory. Similarly, the system is tested for the different defuzzification methods, and based on the results, the centroid method elicits the best possible system response.

Keywords: Fuzzy Logic, Fuzzy Set Theory, Multi-Machine System, Power System Stabilizer, Different De-fuzzification Methods, Simulink

1. Introduction

In the late 1950s and early 1960s, most of the new generating units added to electric utility systems were equipped with continuously acting voltage regulators. As these units came to constitute a large percentage of generating capacity, it became apparent that the voltage regulator action had a detrimental impact on the dynamic stability (or, perhaps more accurately, steady state stability) of the power system. Oscillations of small magnitude and low frequency often persist for long periods of time and in some cases, can hinder power transfer capability. Power system stabilizers (PSSs) have been developed to aid in damping these oscillations via modulation of the generator excitation.

Generally, power systems are nonlinear and the operating conditions can vary over a wide range. In recent years, small signal stability of power systems has received much attention. The main reasons for this are the increasing size of generating units, the loading of transmission lines, and the use of high speed excitation systems near their limit. Small oscillations that occur in power systems due to dynamic load changes and action of controllers, prevent maximization of available generating capacity.

Conventional PSS (CPSS) are used to damp out small oscillations and have been designed based on a model, which is linearized around a particular operating point [1]. The structure and parameters provide optimal performance at this point. The most widely used CPSS is the lead-lag compensator, where the gain settings are fixed to some specific operating condition by tuning.

The configuration of a power system changes with time. The parameters of the PSS must be re-tuned as frequently as possible so that it can continue to provide the desired performance. A self tuning PSS [2], [3] can provide better dynamic performance over a wide range of operating conditions. However, a self-tuning PSS is difficult to realize because it requires parameter identification, state observation, and feedback gain computation, which is time consuming.

Simple alternate control schemes, such as rule-based [4] and fuzzy logic control [5]-[9], have been proposed to overcome such problems. Of these, fuzzy logic control appears to possess the most advantages, such as less computation time and robustness. Fuzzy logic controller can be expressed by a set of rules, which describe the behavior of the controller using linguistic terms. Fuzzy logic techniques have been found to be better substitutes for conventional control techniques that are based on highly complex mathematical models.

The art and science of applying PSS has developed over the past 40 to 45 years since its first widespread application to the Western systems of the United States. This development has brought an improvement in the use of various tuning techniques and input signals and in the ability to deal with turbine-generator-shaft torsional modes of vibrations [1].

In the past five decades, PSS has been used to provide the desired system performance in conditions that require stabilization. The stability of a synchronous generator depends on a number of factors, such as the setting of auto-

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matic voltage regulator (AVR). Many generators are designed with high-gain, fast acting AVRs to enhance large scale stability and synchronize the generator with the power system during large transient fault conditions. However, the high gain of excitation systems can decrease the damping torque of generator. A supplementary excitation controller, referred to as PSS, has been added to synchronous generators to counteract the effect of high-gain AVRs and other sources of negative damping [2].

To provide damping, the stabilizers must produce a component of electrical torque on the rotor, which is in phase with speed variations. The PSS generates a supplementary stabilizing signal, which is applied to the excitation system or control loop of the generating unit to produce positive damping. The most widely used conventional PSS is the lead-lag PSS, in which the gain settings are fixed at certain values that are determined, under particular operating conditions, to result in optimal performance for that specific condition. However, lead-lag PSS has been shown to give poor performance under different synchronous generator loading conditions [3].

CPSS is widely used in existing power systems and has enhanced power system dynamic stability. The parameters of CPSS are determined based on a linearized model of the power system around a nominal operating point, where they can provide good performance. Given that power systems are highly non-linear with configurations and parameters that change with time, the CPSS design based on the linearized model of the power system cannot guarantee performance in a practical operating environment [4], [5].

To improve the performance of CPSS, numerous techniques have been proposed for their design, such as using intelligence optimization methods, such as simulated annealing, genetic algorithm, Tabu search, fuzzy, neural networks, and many other non linear techniques. Intelligent optimization algorithms are used to determine the optimal parameters for CPSS by optimizing an Eigenvalue-based cost function in the offline mode. Due to the fact that the method is based on a linearized model and the parameters are not updated on-line, the performance of CPSS is not satisfactory during practical operation. Rule-based fuzzy logic control methods are well known for the difficulty involved in obtaining and adjusting the parameters of the rules, especially online. Recent research indicates that more emphasis has been placed on the combined usage of fuzzy logic systems and other technologies, such as neural networks, to add adaptability to the design [6]-[8].

2. Multi-machine Power System Analysis

Analysis of practical power system involves the simultaneous solution of equations consisting of synchronous machines associated excitation system, prime movers, interconnecting transmission network, static and dynamic (motor) loads, and other devices, such as HVDC converters and static var compensators. The dynamics of the machine rotor circuits, excitation systems, prime movers, and other devices are represented by differential equations. The result is that the complete system model consists of large numbers of ordinary differential and algebraic equations [9], [10]. Model 1.0 is assumed for synchronous machines by neglecting damper windings. In addition, the following assumptions are made for simplicity [11], [12]:

1. The loads are represented by constant impedances;
2. Transients saliency is ignored by considering “$x_d = x_q$;”
3. Mechanical power is assumed to be constant; and
4. Single time constant AVR is represented by E_{fd}.

$$\rho E'_{qk} = \frac{1}{T'_{d0k}}[-E'_{qk} + (x_{dk} - x'_{dk})i_{dk} + E_{fdk}]$$

$$\rho\delta_k = \omega_B(S_{mk} - S_{mk0})$$

$$\rho S_{mk} = \frac{1}{2H}[-D_k(S_{mk} - S_{mk0}) + P_{mk} - P_{ek}] - -(1)$$

2.1 State Space model of the Multi-machine System

The state space model of k^{th} machine can be represented as follows [11]:

$$\dot{x}_k = [A_k]x_k + [B_k](\Delta V_{refk} + \nabla V_{sk}) \text{ and } \tag{2}$$

$$y_k = [C_k]x_k. \tag{3}$$

The state space model of the 4-machine 10-bus system shown in Fig. 1 can be obtained using machine data, line data, and load flow [11] given by:

$$\dot{x} = [\overline{A}]x + [\overline{B}](\Delta\overline{V}_{\text{ref}} + \Delta\overline{V}_{\text{s}}), \tag{4}$$

where $\dot{\mathrm{x}} = [x_1, x_2, \ldots\ldots\ldots, x_4]^T$. x_k denotes the states of k^{th} machine given by:

$$\mathbf{y} = [\overline{\mathbf{C}}]\mathbf{x}, \tag{5}$$

where all elements or sub-matrices of 4X4 of the $\overline{\mathbf{A}}$ matrix depend on the network.

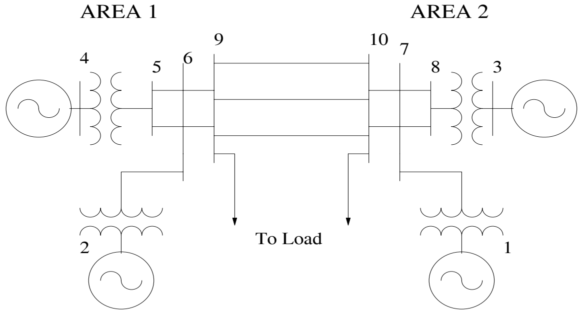

Fig. 1. Block diagram of the 4-Machine 10-Bus System.

3. Fuzzy Logic PSS Structure

The main elements of the Fuzzy Logic PSS Structure (FLPSS) are presented below.

3.1 Fuzzification Unit

Fuzzification is the process of mapping from observed inputs to fuzzy sets in the various input universe of discourse. The observed data are usually in crisp form, and fuzzification is required to map the observed range of crisp inputs to the corresponding fuzzy values for the system input variables. The mapped data are further converted into suitable linguistic terms as labels of the fuzzy sets defined for system input variables.

3.2 Fuzzy Logic Reasoning Unit

The observed values are used to identify the rule used to infer an appropriate fuzzy control action. Point-valued Max-Min fuzzy and Max Product methods can be used by adjusting quality and computational time. Max-Min fuzzy inference method is better than Maximum Product method of inference. Therefore, point-valued Max-Min fuzzy inference method is used in this study.

3.3 Knowledge Base

The knowledge base consists of a database and a rule base.

The database provides the necessary definitions of the fuzzy parameters as fuzzy sets with membership functions defined on the universe of discourse for each variable, while the rule base consists of fuzzy control rules intended to achieve the control objectives.

3.4 Defuzzification Unit

Defuzzification is the process of mapping from a space of inferred fuzzy control actions to a space of non-fuzzy (crisp) control actions. A defuzzification strategy is aimed at producing a non-fuzzy control action that best represents the possible distribution of the inferred fuzzy control action. In this study, each of the input and output are Gaussian membership functions, and there are five membership functions. The chosen universe of discourse is + 1 to – 1. The speed deviation and its derivative are chosen as inputs to the FLPSS. The stabilizer was placed on all four machines as shown in Fig. 2. Fig. 3 shows the Block Diagram of the Fuzzy Logic Controller.

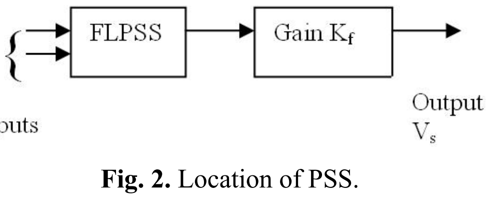

Fig. 2. Location of PSS.

4. Selection of Input Signals of FLPSS

The first step in designing an FLPSS is to decide which state variables representing system dynamic performance must be taken as input signals to FLPSS. The selection of proper linguistic variables in formulating fuzzy control rules is very important in the performance of fuzzy controllers. In the present investigation, generator speed deviation $\Delta\ \omega$ and acceleration $\Delta\varpi$ were chosen as input signals to FLPSS. In practice, only shaft speed deviation $\Delta\omega$ is readily available. Acceleration signal can be derived from speed signals measured at two sampling instances by the following expression:

$$\Delta\,\dot{\omega} = \frac{[\,\Delta\omega(kT) - \Delta\omega(k-1)T]}{T}. \tag{6}$$

In case of CPSS, speed-based PSS is selected because power-based PSS has some problems. First, the phase characteristic of the overall PSS is somewhat limited and cannot be easily tailored to match complex machine-system transfer functions. Second, and most important, power-based stabilizers-whether using only electrical power or power combined with speed-require some compensation to prevent large terminal voltage changes from occurring whenever the mechanical power changes. This frequently limits the maximum practical gains that can be derived using these stabilizers.

5. Membership Function

After choosing proper variables for input and output of fuzzy controllers, it is important to decide the linguistic variables. The linguistic variables transform the numerical values of the input of the fuzzy controllers to fuzzy values. The number of these linguistic variables specifies the quality of control, which can be achieved using fuzzy controller. As the number of linguistic variables increases, the quality of control increases at the cost of increased computer memory and computational time. Therefore, a compromise between the quality of control and computational time is needed to choose the number of variables. For the power system under study, five linguistic variables for each of the input and output variables were used. The linguistic variables are labeled as shown in Table 1.

Table 1. Input and output linguistic variables

LN	Large Negative
MN	Medium Negative
Z	Zero
MP	Medium Positive
LP	Large Positive

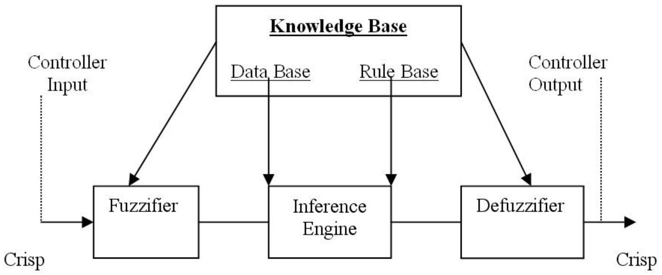

Fig. 3. Block Diagram of Fuzzy Controller.

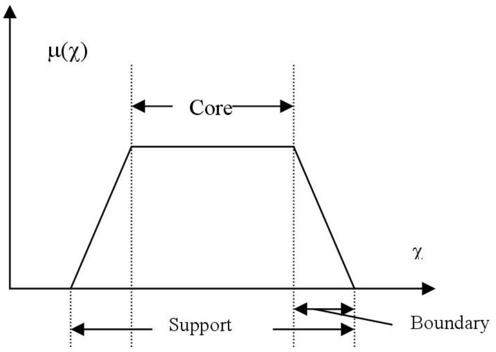

Fig. 4. Sample Membership Function.

All the investigations were carried out considering Gaussian membership functions. A Gaussian membership is defined as:

$$f(x,\sigma_i,c_i) = \frac{e^{-(x-c_i)^2}}{2\sigma_i^2}.$$

A membership function provides information about the fuzziness of a fuzzy set. Fig. 1 illustrates a sample membership function. As can be seen, the core of a membership function is the region in the universe, which is characterized by full membership in the set. This means that in this range of values, the variable is considered to have the property indicated by this membership function. The support is the total region of non-zero membership function. The boundary of a membership function is a region in the universe characterized by some non-zero membership values but not complete membership. In this range of values, the variable is considered to have the property to a certain degree but not fully.

The linear triangular membership function is used in the design of FPSS. Here, the widths of the membership function W_L (Fig. 5) for both $\Delta\omega$ and $\Delta\varpi$ were chosen to be equal for all the labels to keep the number of parameters optimized.. The Rule Table below gives a complete set of rules that define the relation between the inputs and outputs of FPSS. The Rule Table was then transformed into a fuzzy relation matrix [6]. The stabilizer output was determined using Min-Max composition rules (Table 1).

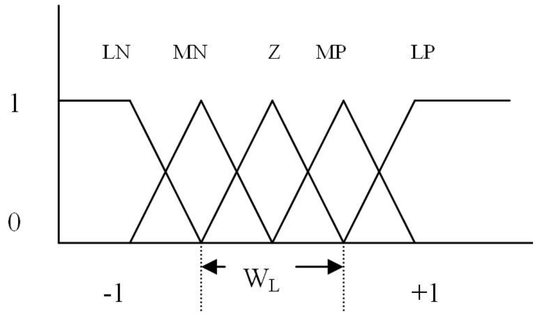

Fig. 5. Linear triangular membership function.

6. Rule Base

The two inputs, speed deviation and acceleration, result in 25 rules for each machine. The Decision Table shows the result of 25 rules, in which positive control signal is for deceleration control and negative signal is for acceleration control. Rule 1: "*If speed deviation is LP (large positive) AND acceleration is LN (large negative), THEN PSS output of fuzzy is Z (zero).*" The stabilizer output was obtained by applying a particular rule expressed in the form of membership function. There are different methods for finding the output, and of these, Min-Max and Maximum Product methods are among the most important. The Min-Max method is used in this study. Finally, the output membership function of the rule is calculated. This procedure is carried out for all rules, and an output membership function is obtained in every rule.

Table 2. Decision table for PSS output

Accel.→ Speed dev.↓	LN	MN	Z	MP	LP
LP	Z	Z	MP	MP	LP
MP	MN	Z	Z	MP	MP
Z	MN	Z	Z	Z	MP
MN	MN	MN	Z	Z	MP
LN	LN	MN	MN	Z	Z

Given that a non-fuzzy signal is needed for the excitation system by identifying the membership function of the fuzzy controller, its numerical value should this be determined. There are different techniques for defuzzification of fuzzy quantities, such as the Maximum Method, Height Method, and Centroid Method. This study uses the Centroid Method.

7. Location of Fuzzy PSS

In a multi-machine power system, stabilizers are located at machines, in which the rotor swing mode is poorly damped. Theoretically, it is possible to have an FPSS at each machine. Such placement of stabilizers would lead to high stabilizer gains that would result in severe deviation in voltage profile under disturbed conditions. In some cases, the stabilizer may even cause leading power factor operation of generators. There are only a few places where the FPSS would result in better damping of all rotor modes. Setting the FPSS at the best location is important in obtaining a stable closed-loop system with well damped rotor modes and small stabilizer gain. The concept of participation factor [10] is used to determine the best location of FPSS.

8. Case Study

8.1 Fuzzy with Robust Multi-machine

Non-linear differential equations governing the behavior of a power system can be linearized about a particular operating point to obtain a linear model, which represents the small signal oscillatory response of a power system. Variations in the operating conditions of the system result in variations in the parameters of the small signal model. A given range of variations in the operating conditions of a particular system thus generates a set of linear models, each corresponding to a particular operating condition. Since, at any given instant, the actual plant could correspond to any model in this set, a fuzzy logic controller would have to import adequate damping to linear model.

A Simulink-based block diagram, including all the nonlinear blocks was generated using machine and line data and load flow as shown in Fig. 6. The speed deviation and acceleration of the machine were taken as outputs, and the initial value of slip was taken as zero. Fuzzy logic-based output slip signal was also used to provide additional damping. Fuzzy logic-based output slip signal damps out the small signal disturbances by modulating the generator excitation. The output must be limited to prevent the PSS from countering the action of the AVR. Different outputs for different generators were also considered. The disturbances considered self-clear faults at bus 3. Figs. 7-10 show the responses of particular generators without PSS and with fuzzy logic PSS. As shown in Fig. 7, the proposed controller takes 10-12 seconds to damp out the oscillations after clearing the fault for Generator 1. According to Fig. 8, the controller took 7-9 seconds to damp out the oscillations for Generator 2. Fig. 9 shows the response for Generator 3, which takes 6-7 seconds to damp out the oscillations, and Fig. 10 shows the response for Generator 4, which takes 12-13 seconds to damp out the oscillations.

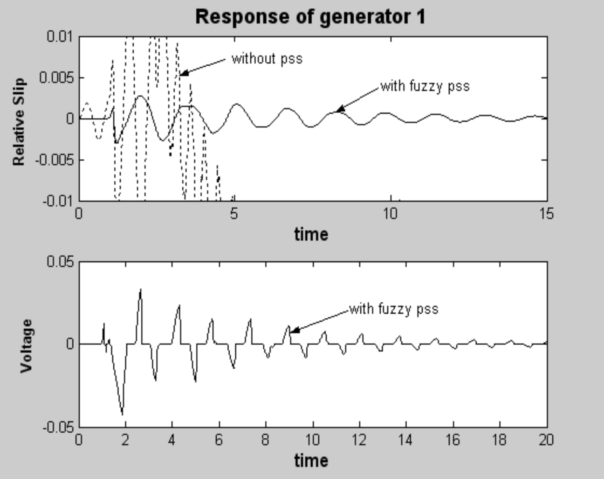

Fig. 7. Response of Generator 1without PSS and with fuzzy logic-based PSS (time is in seconds).

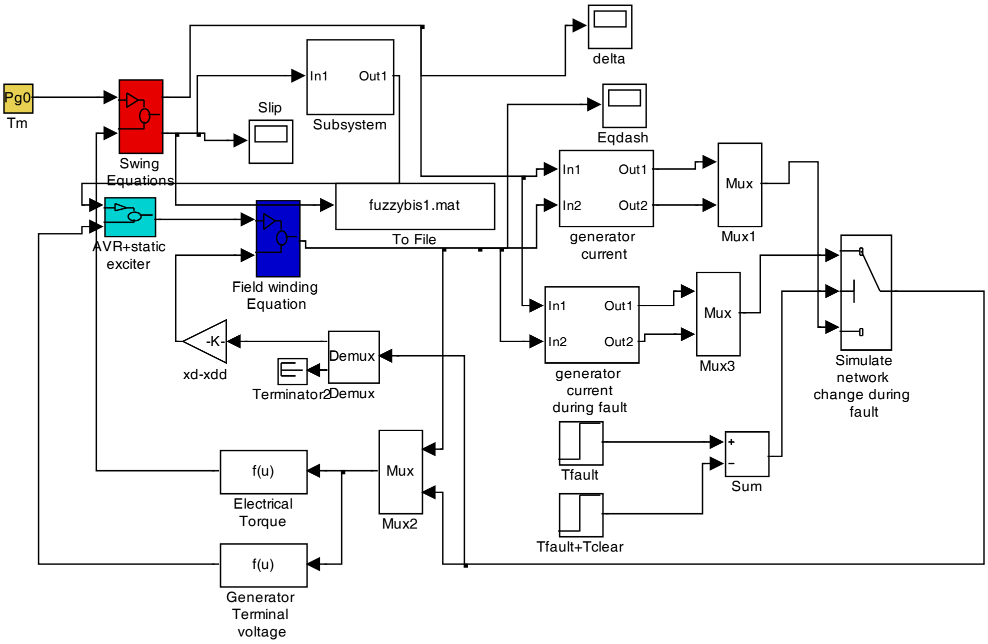

Fig. 6. A Simulink Block Diagram.

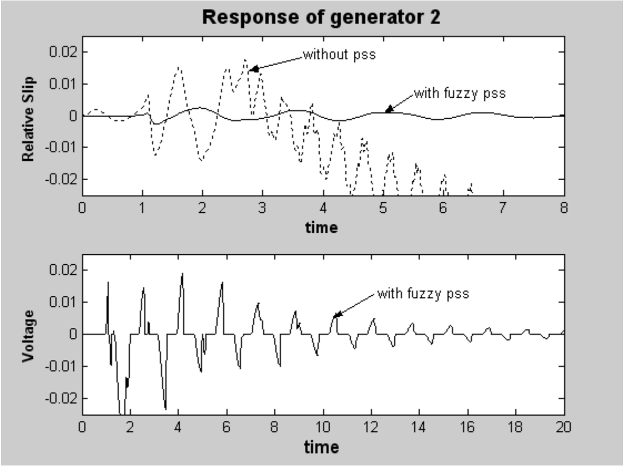

Fig. 8. Response of Generator 2without PSS and with fuzzy logic-based PSS (time is in seconds).

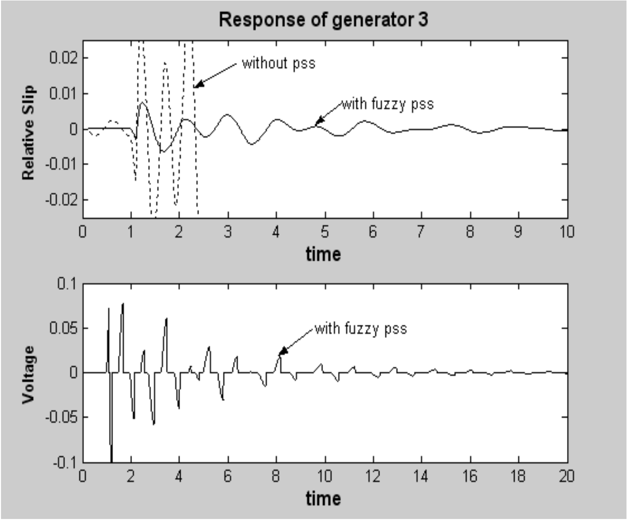

Fig. 9. Response of Generator 3without PSS and with fuzzy logic-based PSS (time is in seconds).

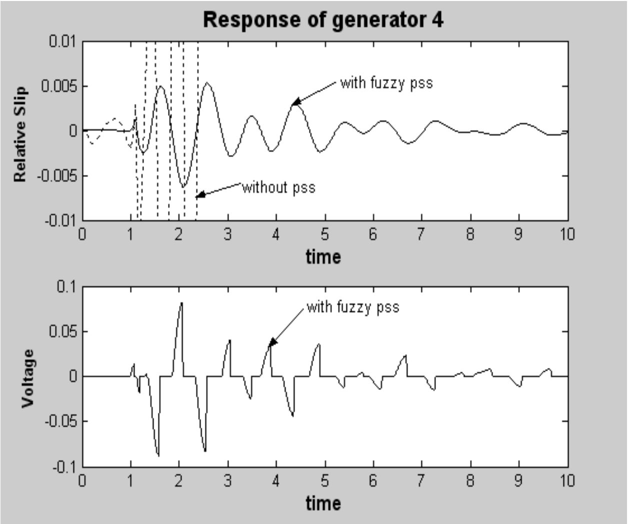

Fig. 10. Response of Generator 4 without PSS and with fuzzy logic-based PSS (time is in seconds).

8.2 Fuzzy with Different Defuzzification Methods with a Multi-Machine

A Simulink-based block diagram, including all the nonlinear blocks, was generated using machine and line data and load flow as given in [11]. The speed deviation and acceleration of the machine were taken as outputs and the initial value of slip was taken as zero. The fuzzy logic-based output slip signal was used to provide additional damping. Fuzzy logic-based output slip signal damps out the small signal disturbances by modulating the generator excitation. The output must be limited to prevent the PSS from countering the action of AVR. Different outputs for different generators are considered. The disturbances self-clear faults at bus 3.

In this analysis, a design scheme fuzzy logic PSS for multi-machine (4 generators) power system with 10 buses was developed. Speed deviation and acceleration of synchronous generator were taken as input signals to the fuzzy

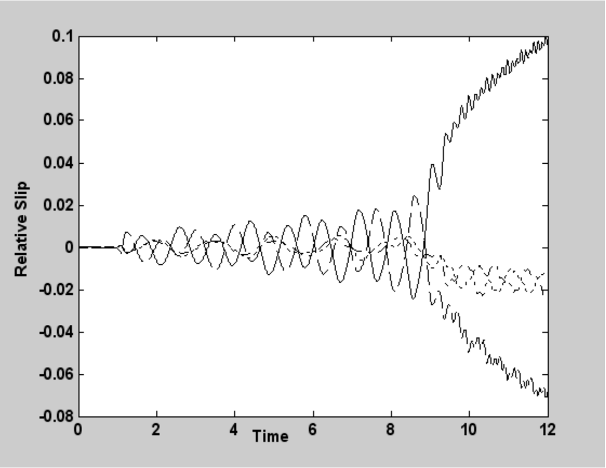

Fig. 11. Response of 4 machines connected to a 10-bus power system when fuzzy logic PSS uses BISECTOR as the defuzzification method.

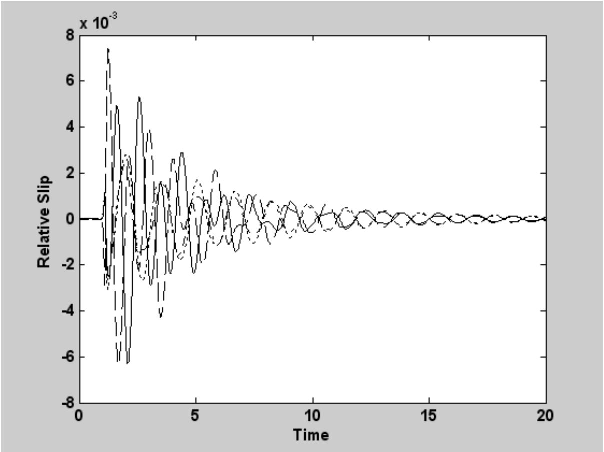

Fig. 12. Response of 4 machines connected to a 10-bus power system when Fuzzy Logic PSS uses CENTROID as the defuzzification method.

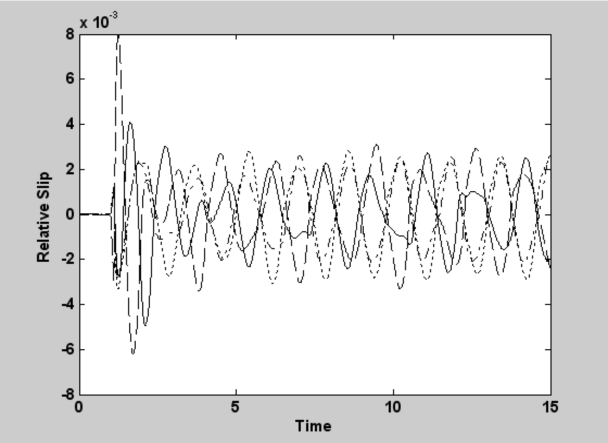

Fig. 13. Response of 4 machines connected to a 10-bus power system when fuzzy logic PSS uses LOM as the defuzzification method.

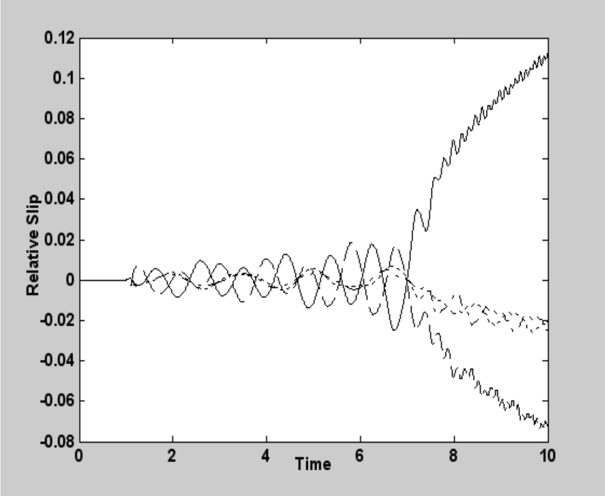

Fig. 14. Response of 4 machines connected to a 10-bus power system when fuzzy logic PSS uses MOM as the defuzzification method.

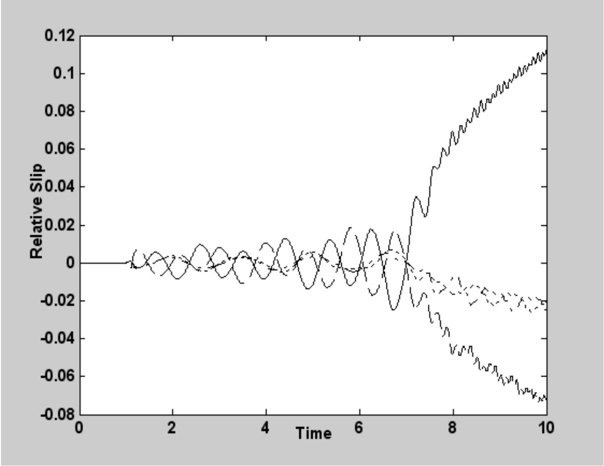

Fig. 15. Response of 4 machines connected to a 10-bus power system when fuzzy logic PSS uses SOM as the defuzzification method.

logic controller. The fuzzy logic controller was then applied to a PSS. The system with fuzzy logic PSS was able to damp out the oscillations at around 15-17 seconds with “Centroid” as the defuzzification method after clearing the fault. The controller was also able to damp out the oscillations at around 25-28 seconds with “LOM” as the defuzzification method after clearing the fault. “Centroid” defuzzification method elicited the best possible response in the system. Simulation results also show that fuzzy logic PSS decreases maximum overshoot and settling time of the response. The control signal, required in all cases, has less magnitude.

9. Conclusions

In this paper, a design scheme fuzzy logic PSS for multi-machine (4 generators) power system with 10 buses was developed. Speed deviation and acceleration of synchronous generator were taken as input signals to the fuzzy logic controller. The fuzzy logic controller was applied to a PSS. The system with fuzzy logic PSS was better since it was effective for all test conditions. Simulation results showed that the fuzzy logic power system stabilizer can decrease maximum overshoot and settling time. The total control signal required should be with lesser magnitude.

The designed fuzzy controller provided good damping enhancement for various operating points of multi-machine (4 generators) power system with 10 buses. The proposed method resulted in better response behavior in terms of damping the oscillations out.

In this study, a design scheme fuzzy logic PSS for multi-machine (4 generators) power system with 10 buses was developed with different defuzzification systems. With these defuzzification methods, simulation results showed that the fuzzy logic PSS can decrease maximum overshoot and settling time of the response. Furthermore, centroid defuzzification method elicited the best possible response of the system.

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