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An Adaptive Fuzzy-Logic Stabilizer for Single and Multi-Machine Power Systems

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Abstract: This paper introduces a fuzzy controller as a power system stabilizer used to damp inter-area modes of oscillation following disturbances in power system. The fuzzy-logic power system stabilizer (FPSS) has been designed to provide a supplementary signal to the excitation system of the synchronous generator. The performance of FPSS, which is tuned automatically as the operating conditions of power system change, is investigated by applying it to a single machine and multi-machine including four machines in two areas of power system. Three proposed types of fuzzy control algorithms are reviewed and tested in these cases, for various types of disturbance. To show the effectiveness of the proposed controller in damping oscillations a three-phase short circuit condition under various loading conditions is presented to illustrate the application of the developed methodology. The obtained results show that the proposed controller for stabilizing power system can provide very good damping characteristic, in comparison with the conventional PSS, through wide range of operating condition for power system and improves dynamic operating of the system substantially.

Key words: Index Terms · Fuzzy control · Power system stabilization · Operating condition

INTRODUCTION

Low frequency oscillations contain local area modes and inter-area modes. Inter-area modes of oscillations may be caused by the either high gain exciters or heavy power transfer upon weak tie line. The occurrence of the inter-area oscillations depends on several reasons such as weak ties between interconnected areas, voltage level, transmitted power and load. The frequency range of the inter-area oscillations is approximately from 0.1 to 1 Hz. It's identifying with the dynamic power transfer between areas. So, the oscillations may continue to grow causing the instability of the power system [1,2].

The most effective way of damping the LFO is the installation of power system stabilizer (PSS). The action of PSS is to enhance angular stability limits of a power system by providing supplemental damping to the rotor oscillations through generator excitation. This damping is prepared by an electric torque applied to the rotor that is in phase with the speed variation.

The parameters of the conventional controllers (fixed-gain, lead-lag and PID PSS) are settled off-line at a nominal operating point to achieve good performance. However, the system dynamic response may regress when the operating point changes to some extent [3]. In addition the power systems are highly nonlinear and the operating conditions could change over a wide range as a result of load changes, line switching and unforeseeable major disturbances such as three phase faults. Thus a controller must be working in the nonlinear systems and providing good damping characteristics over a wide range of operation conditions such as fuzzy controller. Fuzzy controller has many advantages. They are simple in structure and relatively easy to realize mathematical model of the controlled system. The variations of the parameters and operating conditions of the controlled system do not significantly affect the performance of the controller.

P. Mitra proposed the application of a new input signal based fuzzy power system stabilizer in multi-machine system. He used the deviation of active power through the tie line connecting two areas as one of the inputs to the fuzzy PSS in conjunction with the speed deviation [4]. Junya Mtsuki described the experimental results on an application of fuzzy control design to stabilization of electric power systems [5]. Y.J. Cheng presented an integrated tabu-fuzzy knowledge based controller applied to enhance the performance of power system stabilizer (PSS) [6]. T. Hussein introduced a robust adaptive fuzzy controller as a power system stabilizer (RFPSS) used to damp inter-area modes of oscillation

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following disturbances in power systems [7]. A.L. Elshafei proposed a new power system stabilizer based on adaptive fuzzy systems, that has the ability to adaptively tune its rule-base online [8]. A.A. Abou El-Ela proposed a multi-stage procedure to overcome the effects of different emergency conditions using multi-objective fuzzy linear programming (MFLP) technique [9]. T.S. Chung investigated a strange control strategy is developed for High Voltage DC (HVDC) links to enhance oscillatory stability of interconnected power systems [10].

Now, in this paper, we concern about the fuzzy controller abilities in power systems. It will be shown that the proposed controller for stabilizing power system can provide very good damping characteristic, in comparison with the conventional PSS.

Fuzzy Control Algorithms: The linear control theory uses a mathematical model of a plant and some specifications of the anticipated behavior in closed loop to design a controller .These controller are favorably used and have a good behavior in systems that can be supposed as linear in specific range of their operation and pre-determined conditions. The method of root-locus design was tried in the linear control design and because of having non-acceptable results, would not be deal with profundity in this paper, due to the difficulty to achieve a mathematical model as in numerous nonlinear or unknown systems. In some cases, system does not have constant parameters or has interdependence with others parameters. In these cases, the linear control strategies could be limit in its design and performance. These reasons cause that the human knowledge adds various types of information and mix different control strategies that cannot be added in an analytical control law and do not need an accurate mathematical model. The Knowledge-based fuzzy control uses the experience and the knowledge of a proficient about the system behavior. A kind of Knowledge-based fuzzy control is the rule-based fuzzy control, where the human knowledge is approached by means of linguistic fuzzy rules in the form *if-then,* which describes the control action in a special condition of the system. Due to the nonlinear behavior exhibited by the machine, designing a linear control is not successful. By knowing the advantages of the fuzzy control, described before, a nonlinear fuzzy control might be desirable as a power system stabilizer, instead of PSS, by providing a supplementary signal to the excitation system of the synchronous generator. The control proposed for the controller is a Mamdani controller, since it is usually used as feedback controller because the rule base represents a static mapping between the preceding and the consequent variables. For stabilizing power system in a fuzzy controller, the Fuzzy Inference System (FIS) uses the error and/or error derivative as input and the supplementary signal that inject to excitation system of the synchronous generator, as output.

The fuzzy logic controller unlike conventional controllers does not require a mathematical model of the process. However, a understanding of the system and the control requirements is necessary. The fuzzy controller designer must clarify how the information is processed (control strategy and decision) and information flows out of the system (solution/output variable). The fuzzy logic controller consists of three basic blocks: 2.1) Fuzzification; 2.2) Inference Mechanism; 2.3) Defuzzification

Fuzzification: The fuzzy logic controller requires that each control variables which define the control surface be described in fuzzy set symbols using linguistic rules. To decompose each system variables into fuzzy domain, the membership functions must be defined. The membership functions symbolize the extent that which variable is a member of a particular rule. This procedure of converting input/output variables to linguistic rules is designated as Fuzzification that is performed using the rule bases. The control rules are constructed based on the characteristics of the step response. For example, if the output is falling far away from the set point, a large control signal that pushes the output toward the set point is awaited, since a small control signal is required when the output is near and approaching the set point.

Inference Mechanism: the behavior of the control surface which explains the input and output variables of the system, is managed by a set of rules. A characteristic of rules would be: If (*fuzzy suggestion*) Then (*fuzzy suggestion*) Where the fuzzy suggestion is of the type "*x is y*" or "*x is not y*", *x* being a scalar variable and *y* is a fuzzy set associated with that variable. These rules are used to decide the proper control action. When a set of input variables are read, each of the rules that has any grade of truth (a nonzero value of membership grade) in its premises is fired and cause to creating of the control surface by properly adapting it. When all the rules are fired, the resulting control surface, described as a fuzzy set to represent the controllers output. These rules used to create a fuzzy set that semantically represents the concept associated with the rule. To have a smooth, stable control surface, an overlap between adjoining rules is provided such that the sum of the vertical points of overlap should never be greater than one. In the proposed controller the error and/or error derivative is fuzzified and described as fuzzy sets.

Defuzzification: The fuzzy set that depicting the controller output in linguistic rules has to be transformed into a feasible solution variable before it can be used to control the system. This is obtained by using a Defuzzification. Various methods of Defuzzification are available. The most prevalently used methods are a) Mean of Maxima (MOM) and b) Center of Area (COA). COA method is used in this paper, because this method calculates the center of gravity of the final fuzzy space and products a result which is sensitive to all the rules performed. Hence the results tend to move smoothly across the control surface.

The three types of fuzzy control algorithms presented in this paper: a) a single input-single output control scheme, b) another single input-single output control scheme and c) two input-single output control scheme.

Single Input-single Output Control Scheme (Type 1): In the type (1) controller, the acceleration of generator speed is chosen as input and output of the controller is used as a supplementary stabilizing signal, instead of PSS, to the AVR of the tested generator. The accelerating control of the study system is achieved by applying a positive stabilizing control signal U to the excitation loop, while the decelerating control is achieved by applying a negative stabilizing control signal U to the excitation loop. Regarding these, the control rule may be described as fuzzy conditional statements as follows: "if the speed derivative is negative, then the applied control signal is negative" and "if the speed derivative is positive, then the applied control signal is positive". Thus at least two rules are needed. To realize a more efficient control, a set of seven rules are determined in this study as follows where PL (positive large), PM (positive medium), PS (positive small), ZR (zero), NS (negative small), NM (negative medium), PB (positive big) and NL (negative large).

Rule 1: if $d\acute{\omega}$ is NL then U is NL.
Rule 2: if $d\acute{\omega}$ is NM then U is NM.
Rule 3: if $d\acute{\omega}$ is NS then U is NS.
Rule 4: if $d\acute{\omega}$ is ZR then U is ZR.
Rule 5: if $d\acute{\omega}$ is PS then U is PS.
Rule 6: if $d\acute{\omega}$ is PM then U is PM.
Rule 7: if $d\acute{\omega}$ is PL then U is PL.

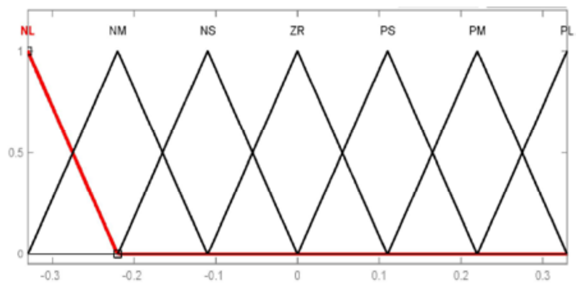

Fig. 1: Membership Function of dþ in type (1) fuzzy controller

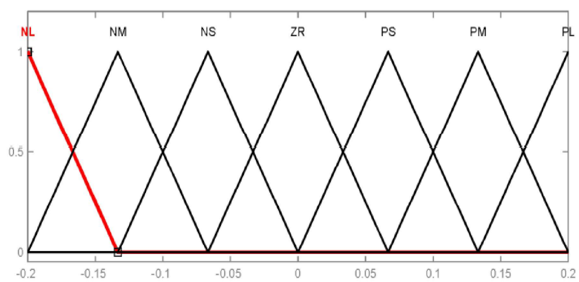

Fig. 2: Membership Function of output in type (1) fuzzy controller

For each of these fuzzy sets, triangular membership function (MF) has been used. These membership functions are shown in Figs. 1, 2.

Single Input-single Output Control Scheme (Type 2): In the type (2) controller, the time derivative of rotor speed of generator þ is chosen as input and signal U is the output of the controller. Seven fuzzy subsets have been used in this scheme similar type (1) controller. A set of seven rules are determined in this study as follows. For each of these fuzzy sets, triangular membership function (MF) has been used. These membership functions are shown in Figs. 3, 4.

Rule 1: if $\acute{\omega}$ is NL then U is NL.
Rule 2: if $\acute{\omega}$ is NM then U is NM.
Rule 3: if $\acute{\omega}$ is NS then U is NS.
Rule 4: if $\acute{\omega}$ is ZR then U is ZR.
Rule 5: if $\acute{\omega}$ is PS then U is PS.
Rule 6: if $\acute{\omega}$ is PM then U is PM.
Rule 7: if $\acute{\omega}$ is PL then U is PL.

A Two Input- Single Output Control Scheme (Type 3): In the type (3) controller, the acceleration of generator speed ($d\acute{\omega}$) and the Rotor speed deviation ($d\acute{\omega}$) are selected as inputs and the supplementary stabilizing signal U is the output of the controller.

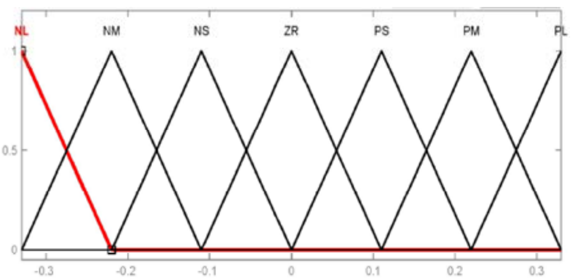

Fig. 3: Membership Function of þ in type (2) fuzzy controller

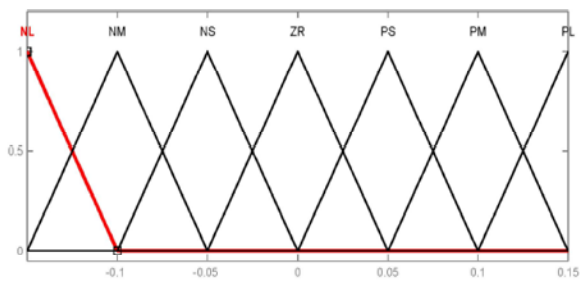

Fig. 4: Membership Function of output in type (2) fuzzy controller

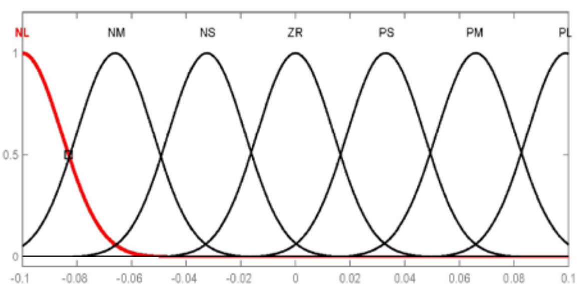

Fig. 5: Membership Function of dù in type (3) fuzzy controller

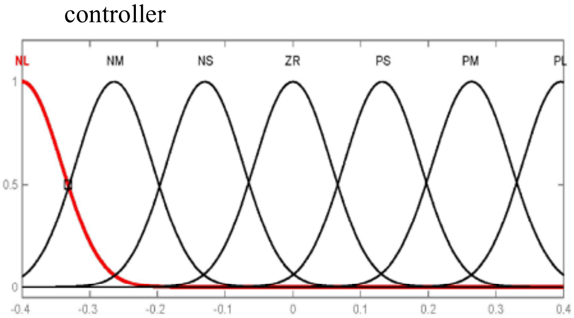

Fig. 6: Membership Function of [illegible] in type (3) fuzzy controller

The interval of the membership functions should be determined by trial and error, using the simulation of system to achieve optimum performances. Seven fuzzy subsets have been used in this scheme similar type (1). For each of these fuzzy sets, Gaussian membership

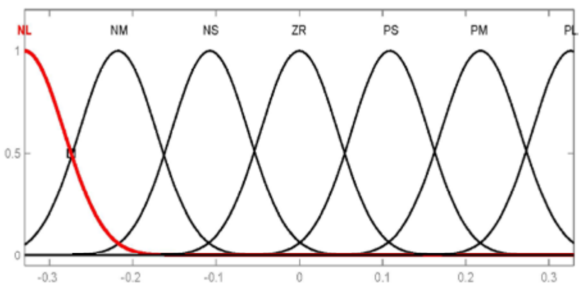

Fig. 7: Membership Function of output in type (3) fuzzy controller

Table 1: fuzzy control rules

dω/dώ	NL	NM	NS	ZR	PS	PM	PL
NL	NL	NL	NL	NM	NS	NS	ZR
NM	NL	NM	NM	NM	NS	ZR	PS
NS	NL	NM	NS	NS	ZR	PS	PM
ZR	NL	NM	NS	ZR	PS	PM	PL
PS	NM	NS	ZR	PS	PS	PM	PL
PM	NS	ZR	PS	PM	PM	PM	PL
PL	ZE	PS	PS	PM	PL	PL	PL

function (MF) has been used. These membership functions are shown in Figs.5, 6, 7. 49 fuzzy subsets results through these fuzzy sub-sets for computing the output is shown in table 1.

System Description: The model of system, consists of a 200^{MVA}, 13.8^{KV} Three phase, 60^{Hz}, 32 pole synchronous generator. The generator is connected to the network (10000^{MVA}, 230^{KV}) through a transmission line, as shown In Fig.9. The basic parameters of the generator are shown in the appendix. The generator is equipped with an AVR and a PSS. Fig.17. shows the multi-machine power system which is used in simulation studies. The test system [11] consists of two fully symmetrical areas linked together by two 230 KV lines of 220 Km length. It was particularly designed in [11] to study low frequency electromechanical oscillations in large interconnected power systems. Though its small size, it follows very closely the behavior of a typical system in actual operation. Each area is equipped with two same round rotor generators rated 20 KV/900 MVA. The synchronous machines have same parameters except for the inertias which are H = 6.5s in area 1 and H = 6.175s in area 2.

Implementation of Fuzzy Control: The proposed methodology is first confirmed for a single-machine-connected to network in Section 4.1, where the simulated result is compared with the conventional PSS.

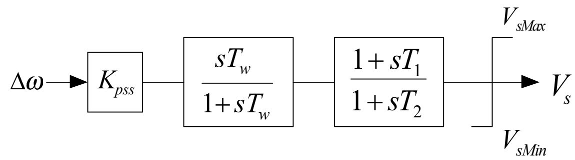

Fig. 8: Block diagram of the PSS

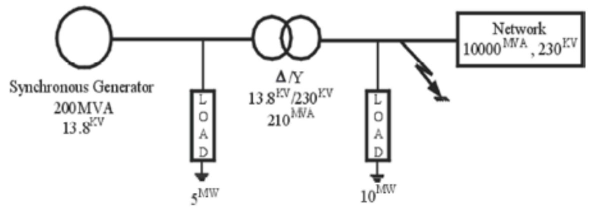

Fig. 9: The model of Single-machine- connected to the network

In Section 4.2, the accuracy and effectiveness of the methodology are investigated for a four-machine two-area power system. The curves shown for the multi-scale simulation have been obtained with the synchronous machine modeled in the dq0 domain.

Single-machine- Connected to the Network: The single-machine-connected to the network studied is shown in Fig.9. The network parameters are in per unit values base reciprocal per unit system [11]. In steady state, the terminal voltage E_t of the synchronous machine is 1.0<7.11° while it delivers a complex power of 0.75+j0.01pu. The parameters of machine can be obtained from Appendix. To show the design process as well as to investigate the effectiveness of the fuzzy controllers, we set the three phase short circuit faults during [0.5 0.57] of time for two cases, AVR with PSS and AVR with Fuzzy Controller.

System Responses under AVR and PSS: The basic elements designed the excitation system block are the voltage regulator and the exciter. The conventional power system stabilizer (CPSS) block diagram can be used to add damping signal to the rotor oscillations of the synchronous generator by controlling its excitation. The conventional power system stabilizer is modeled by the nonlinear system as shown in Fig.8.

Figs.10, 11 illustrates the dynamic behaviors of the generator following a three phase short circuit faults in the case of AVR with PSS in the one-machine connected to the network. The following variables are plotted: electrical output power (Pe) and rotor speed deviation ($d\hat{\omega}$).

System Responses under Avr and Fuzzy Controller: Figs.10, 11 shows the dynamic behaviors of the system under the type (1) fuzzy controller and AVR, in the one-machine connected to the network. From these figures, it can be seen that the oscillations are more quickly damped than those under AVR and PSS. The dynamic behaviors of the system under the type (2) and (3) fuzzy controller and AVR are shown in these figures.

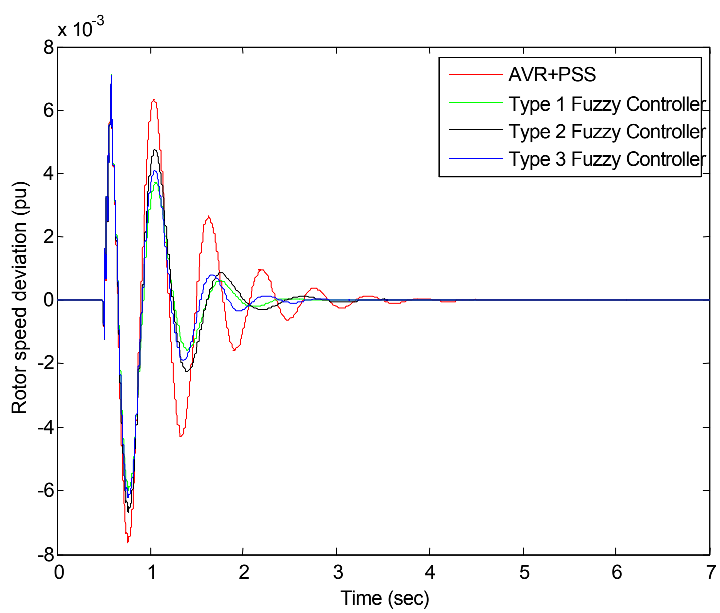

Fig. 10: Rotor speed deviation in four states

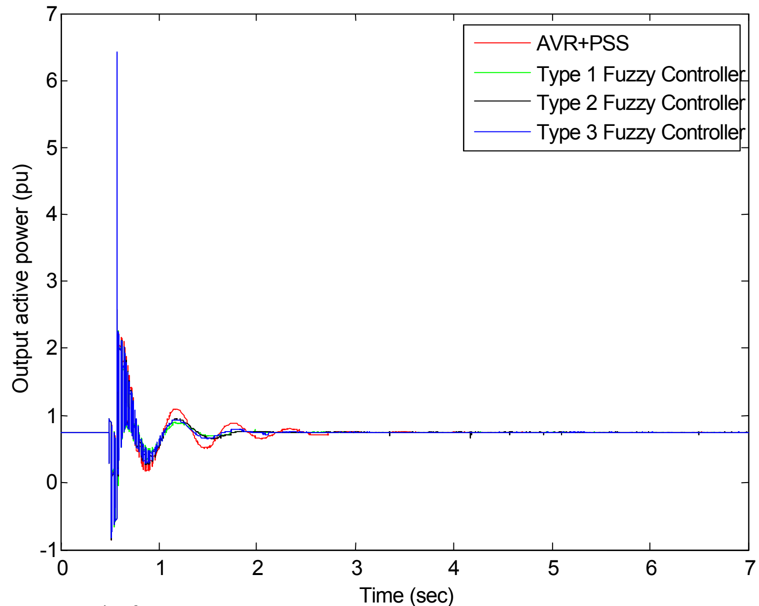

Fig. 11: Output active power in four states

It has been noticed that the performance of type (1) controller, with 7 rules, substantially improve the damping of the generator oscillations, in comparison with the conventional PSS. The results illustrate that a slightly improvement of the system stability was achieved by the type (2) fuzzy controller in comparison with type (1) controller.

However the performance of the fuzzy controller can be improved on the expense of using a significantly larger rule-base. So a considerable improvement of the system stability was obtained by type (3) fuzzy controller, with 49 rules, in comparison with that by the conventional power system stabilizer.

Multi-machine Power System: The four-machine two-area power system from [11] is adjusted to study the power system short circuit as shown in Fig. 17. The transmission lines with lengths of 110 km are represented by the constant distributed parameter model illustrated in [11] and other lines are represented by ð-models. The passive resistive and reactive loads are modeled as constant impedances. The network parameters are achieved from [11, Chapter12].

In order to check the feasibility of type (3) fuzzy controller in the multi-machine power system (Fig.17), a large disturbance caused by a three-phase to ground fault at 10s applied at the middle of one 110 km transmission line between Bus 8 and Bus 9 and cleared after 0.07 sec by opening the breakers at the ends of the faulty line to isolate it. At this time the inter area oscillations between Area 1 and Area 2 begin.

Three membership functions have been used in this scheme similar type (3) controller. The membership functions of $d\acute{\omega}$ for machine 1, 2, 3 and 4 in the range of [-0.006 0.006], [-0.3 0.3], [-0.3 0.3] and [-0.3 0.3] respectively. However the membership functions of for machine 1, 2, 3 and 4 in the range of [-0.004 0.004], [-0.004 0.004], [-0.006 0.006] and [-0.004 0.004] respectively. Finally the membership functions of output for machine 1, 2, 3 and 4 in the range of [-0.4 0.4].

49 fuzzy subsets results through these fuzzy sub-sets for computing the output is shown in table 1. Figs 12-15 show the dynamic behaviors of the system under the type (3) fuzzy controller and AVR, in the multi-machine power system. From these figures, it can be seen that the oscillations are more quickly damped than those under AVR and PSS.

Practical Robustness of the Fuzzy Controller: In this section, we investigate the practical robustness on the basis on the time period of short circuit respect to PSS. The resulting simulation is presented in Fig16.

With the Fuzzy controller, we can increase the duration short circuit until t=10.755sec without loss of stability.

The results demonstrate that the type (3) fuzzy controller show some robustness for the system change in the multi-machine system.

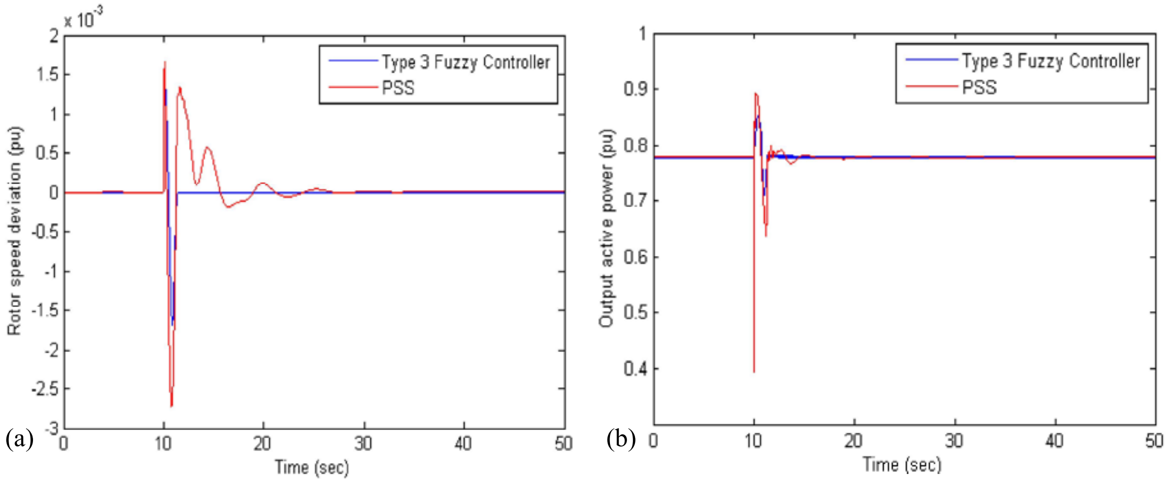

Fig. 12: Responses in Machine 1: (a): Rotor speed deviation (pu) (b): Output active power (pu)

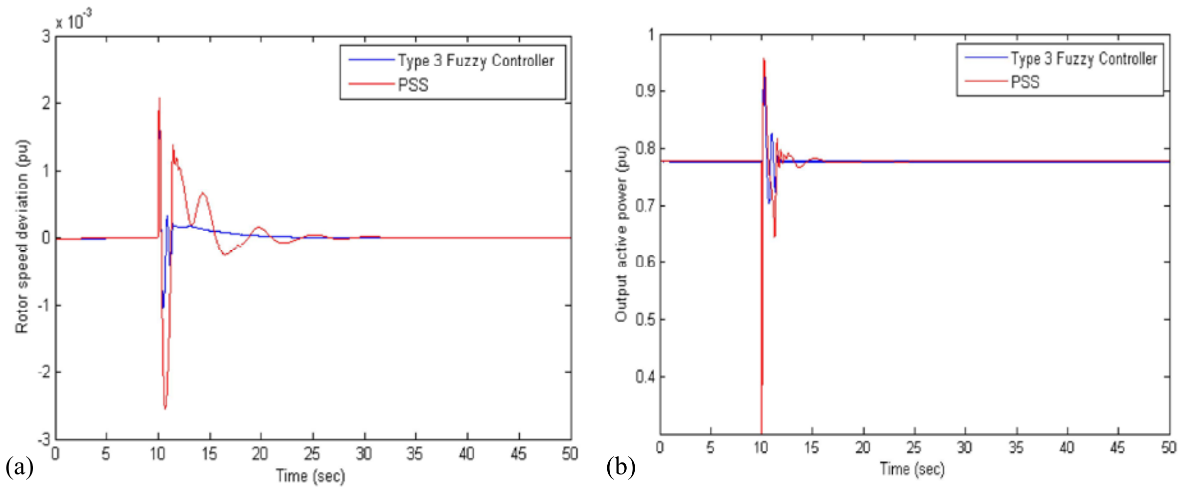

Fig. 13: Responses in Machine 2: (a): Rotor speed deviation (pu) (b): Output active power (pu)

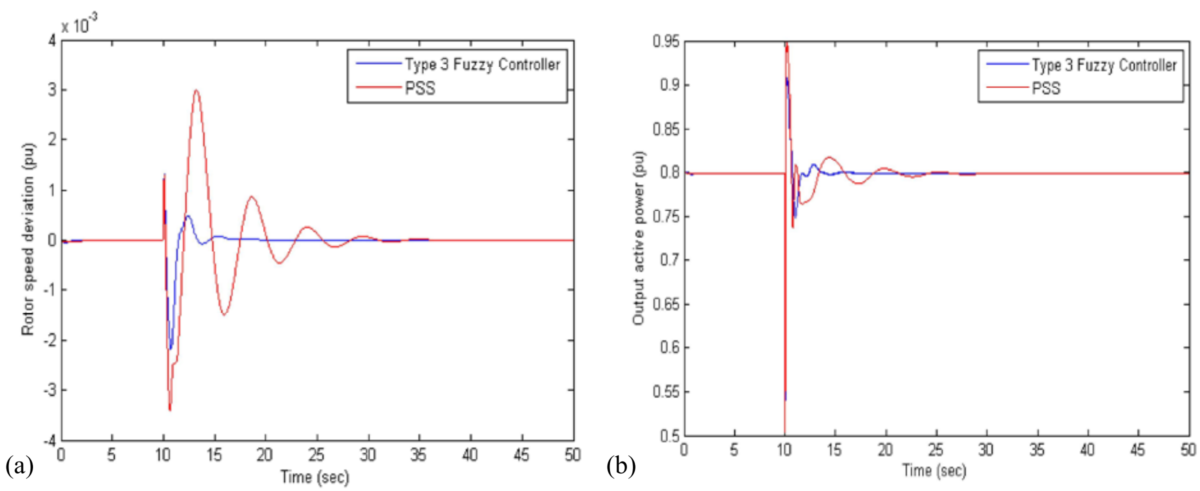

Fig. 14: Responses in Machine 3: (a): Rotor speed deviation (pu) (b): Output active power (pu)

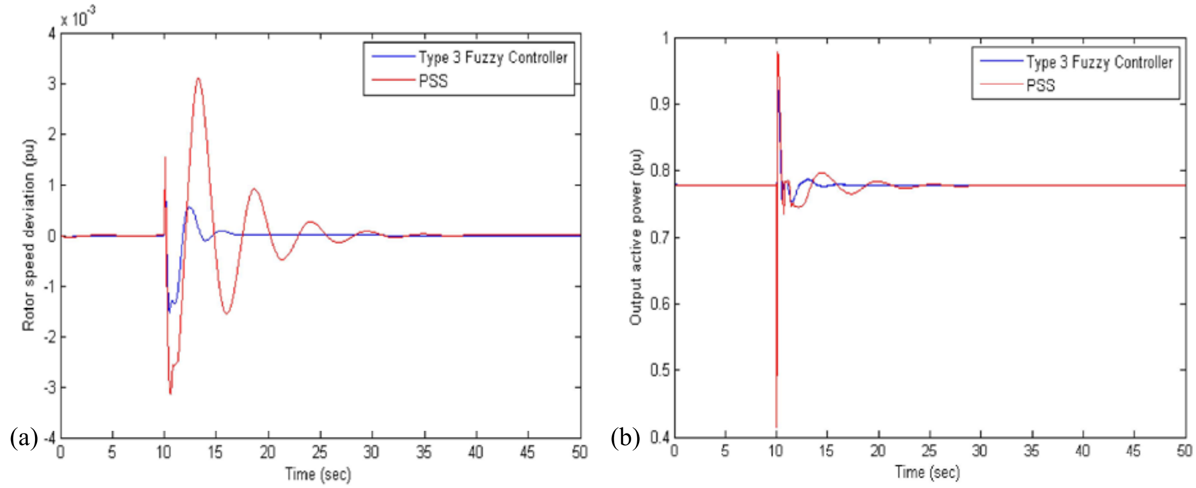

Fig. 15: Responses in Machine 4: (a): Rotor speed deviation (pu) (b): Output active power (pu)

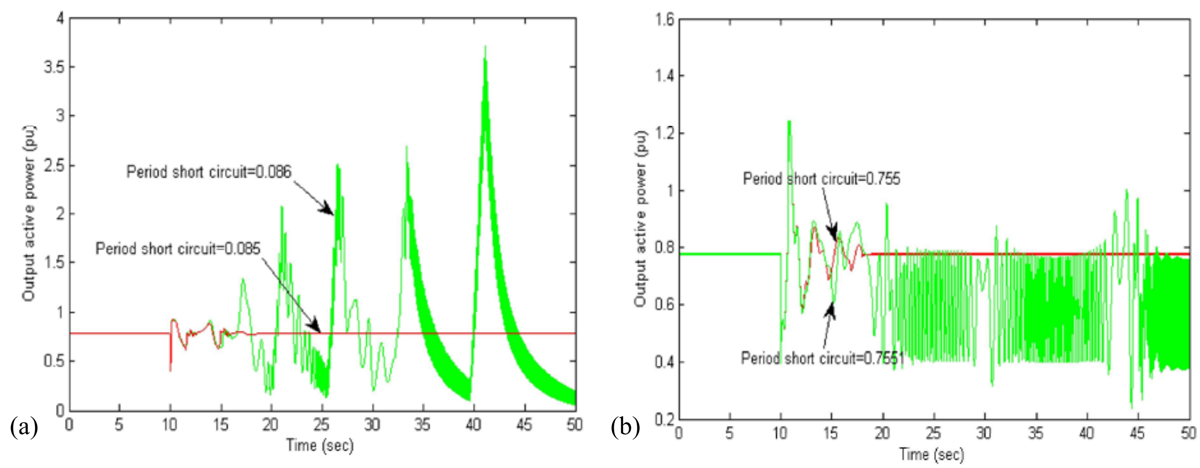

Fig. 16: Output active power for Machine 1 in stability limit analysis of the: (a): PSS (b): Fuzzy controller

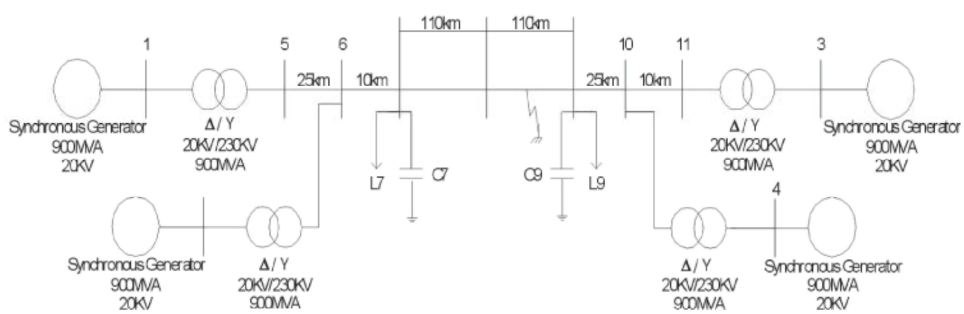

Fig. 17: The model of Multi-machine power system

Performance Index: In order to describe the system dynamic response, the following type performance index is used:

$$J = \int |\Delta\omega| \cdot dt$$

The index J is selected in order to compare the performance of PSS with Fuzzy controller (Table2). The optimal settings of the parameters are determined at the values which minimize the above performance index J. Table2 shows that in all machines the index J through fuzzy controller is improved. So better performance is achieved by fuzzy controller in comparison with PSS.

The Preference of the Proposed Controller Can Be Explained as Follows:

- It follows a smooth gain scheduling design algorithm where a different controller is actually utilized according to the need of the plant.
- uzzy controllers are nonlinear mappings while the CPSS is linear one. This nonlinearity gives more flexibility in shaping the control surface and providing better performance.
- t is observed that system is settled absolutely fast. This justifies the robustness of proposed controller, which is capable to stand up to the changes in dynamic parameters of system.
- lassical controllers such as CPSS have demonstrated not to be efficient enough under practical tests because of the optimization procedure used to setup their parameters.
- ransient performance of dual-input FPSS is better than single- input controller.

CONCLUSIONS

Power systems could lose synchronism if the low frequency inter-area modes of oscillations are not damped effectively. A conventional power system stabilizer can provide sufficient damping for a limited range around its tuning point. To improve the performance of power system stabilizer, fuzzy power system stabilizer (FPSS) has been proposed. The fuzzy controller has been designed to provide a supplementary signal to the excitation system of the synchronous generator. In this paper the control performances of the three proposed fuzzy controllers, insist of PSS, under various operating conditions are investigated. The simulation results of single-machine and four-machine two-area system show that the similar damping control method can effectively damp LFO of multi-machine system under multi-operation modes, enlarge the damping of system and extremely improve the stability of system.

Fig.16 shows that the proposed controller has good disturbance rejection performance and good robust stability against parameter variation, respect to PSS.

The design of the fuzzy controllers requires no mathematical model of generator and power system as would be needed by the conventional power system stabilizers. Regarding this and its simple control scheme also, the performances of the proposed fuzzy controllers were reasonably agreeable. Probably due to their nonlinearity, although determination of optimal fuzzy control parameters by trial and error was required.

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Appendix

Machine Parameters:

The parameters of the tested generator in the case of one-machine connected to network are as follows:

$x_d = 1.305$	$x_1 = 0.18$	$T'_d = 1.01$
$x'_d = 0.296$	$x''_q = 0.243$	$T''_d = 0.053$
$x''_d = 0.252$	$R_s = 2.5\times10^{-3}$	$T''_{q0} = 0.1$
$x_q = 0.474$		$H = 3.2$

The parameters of the generator 1, 2, 3 and 4 in the case of Multi-machine are as follows:

$x_d = 1.8$	$x_1 = 0.2$	$T'_d = 8$
$x'_d = 0.3$	$x''_q = 0.25$	$T''_d = 0.03$
$x''_d = 0.25$	$R_s = 2.5\times10^{-3}$	$T''_{q0} = 0.05$
$x_q = 1.7$		

PSS data:

K_{PSS}	$T_W = 1.41$	$T_1 = 0.154$
$T_2 = 0.033$	$V_{SMax} = 0.2$	$V_{SMin} = -0.2$