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A New Adaptive Fuzzy Pi Control to Stability Control of Power System

[1]Bahman Bahmani Firouzi, [2]Taher Niknam and [3]Hosein Khorsand

[1]Islamic Azad University, Marvdasht Branch, Marvdasht,Iran, P.O. 73711-13119, Marvdasht, Iran.
[2]Islamic Azad University, Marvdasht Branch, Marvdasht, Iran
[3]Electronic and Electrical Engineering Department, Shiraz University of Technology, Shiraz, Iran.

Abstract: This paper introduces a fuzzy PI controller as a power system stabilizer. The fuzzy PI controller has been designed to prepare an auxiliary signal to the excitation system of the synchronous generator. The proposed controller utilizes a combination of a fuzzy logic controller (FLC) and a PI controller. In comparison with the conventional fuzzy controllers, the proposed fuzzy PI controller incorporates the advantages of a FLC and a conventional PI controller. By implementing this controller instead of conventional PSS the damping of local modes of oscillations in a power system will be handled substantially. In addition, the paper considers the conventional PSS and compares its performance with respect to three proposed types of fuzzy PI controller. Also the effects of the supplementary signals in damping oscillation have been shown. Finally, to investigate the effectiveness of the proposed controller in damping oscillations a three-phase short circuit condition is investigated 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.

Key words: Fuzzy control, Power system stabilization, operating condition

INTRODUCTION

Power generators are conventionally provided with automatic voltage regulators (AVRs) to enhance their dynamic responses and control their terminal voltages. But, AVRs introduce negative damping torques, which affect the stability adversely. Since disturbances, such as short circuits and operating point variations of power systems, may exhibit undesirable oscillations or lose synchronism (Yu, Y., 1983). The conventional power system stabilizers (CPSS) are normally incorporated to suppress and damp these oscillations. Other types of PSS such as proportional integral (PIPSS) and proportional integral derivative (PIDPSS) have also been proposed. The gain settings of these controllers are arranged based on the linearized model of the power system around a nominal operating point to achieve optimal performance at this point (Awed-Badeeb, 2006). Generally, the power systems are highly nonlinear and the operating conditions can change over a wide range due to load changes, line switching, and unforeseeable major disturbances such as three phase faults. Therefore a controller must be working in the nonlinear systems and giving good damping characteristics over a wide range of operation conditions. The conventional PI controller with fixed gains has been designed at nominal operating conditions. So it weakens to provide the best control performance over a wide range of operating conditions and show poor dynamic performance. To solve this problem, adaptive-gain-scheduling techniques which are based on the adoption of a fuzzy system for gain scheduling have been proposed (Juang, 2006). Fuzzy PI controllers have many advantages such as they are simple in structure, and relatively easy to realize mathematical model of the controlled system. They provide an effective way to overcome deficient information. They give flexibility in decision making processes and provide an interesting machine interface by simplifying rule extraction from human experts. In addition the variations of the parameters and operating conditions of the controlled system do not substantially affect the performance of the controller, and controller parameters can be changed very quickly by the system dynamics because no parameter estimation is needed in designing controller for nonlinear systems. Therefore a fuzzy PI controller, which represents a model-free type of nonlinear control algorithms, could be a reasonable solution (Demiroren, 2004).

Ghoshal *et al* utilized bacteria foraging optimization (BFO) – a bio-inspired technique to tune the parameters of both single-input and two-input power system stabilizers to achieve the optimal transient performances (Ghoshal, 2009). Mtsuki *et al* described the experimental results on an application of fuzzy

Corresponding Author: Bahman Bahmani Firouzi, Islamic Azad University, Marvdasht Branch, Marvdasht,Iran, P.O. 73711-13119, Marvdasht, Iran.
Email: bahman_bah@yahoo.com Tel: +989177154688

control design to stabilization of electric power systems (Mtsuki, 1991). Cheng *et al* proposed an integrated tabu–fuzzy knowledge based controller applied to enhance the performance of power system stabilizer (PSS) (Cheng, 2003). Hussein *et al* presented a robust adaptive fuzzy controller as a power system stabilizer in damping inter-area modes of oscillation due to disturbances in power systems. He implemented two fuzzy systems. The first system models the nominal values of the system's nonlinearities, and the second system is an adaptive one used for modeling errors (Hussein, 2009). Elshafei *et al* presented a new power system stabilizer based on adaptive fuzzy systems, that has the ability to adaptively tune its rule-base online (Elshafei, 2005). Abou El-Ela *et al* proposed multi-modes of fired fuzzy linguistic rules inside the security regions for different constrained power dispatch (CPD) controller centers (Abou El-Ela, 2007). Chung *et al* investigated a novel control strategy for High Voltage DC (HVDC) links to enhance oscillatory stability of interconnected power Systems (Chung, 2002). Taher *et al* presented a novel robust fuzzy logic power system stabilizer design. He basically uses only one measurable $\Delta\omega$ signal as input (Taher, 2007). But, in none of the above, fuzzy PI controller as a power system stabilizer was not take into consideration. In this paper, we concern about the fuzzy PI 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.

2. 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 controllers are favorably utilized and have a good behavior in linear systems. These systems 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. Since having non-suitable results and difficulty to obtain a mathematical model, would not be deal with in this paper. In some cases, system does not have constant parameters or has interdependence with others parameters. Therefore the linear control strategies would be limit in its design and performance. These reasons cause that the human knowledge add various types of information and mix different control strategies. These strategies cannot be added in an analytical control law and do not need an precise mathematical model. The knowledge-based fuzzy control uses the experience and the knowledge of a adept about the system behavior. A kind of knowledge-based fuzzy control is the rule-based fuzzy control. 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. Because of the nonlinear behavior shown by the machine, designing a linear control is not successful. By knowing the advantages of the fuzzy control, investigated before, a nonlinear fuzzy control might be desirable as a power system stabilizer. The fuzzy controller provides a supplementary signal to the excitation system of the synchronous generator. The control proposed for the controller is a Mamdani controller. 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. However the output of controller is injected to excitation system of the synchronous generator.

The fuzzy logic controller unlike conventional controllers does not need a mathematical model of the system. However, an 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

2.1. 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 dismember each system variables into fuzzy domain, the membership functions must be defined. The membership functions symbolize the domain that which variable is a member of a particular rule. This procedure of transforming 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 needed when the output is near and approaching the set point.

2.2. Inference Mechanism:

The behavior of the control surface which illustrates 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 determine 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 domain is fired and cause to creating of the control surface by properly adapting it. When all the rules are fired, the resulting control surface, is described as a fuzzy set to represent the controllers output. These rules used to produce a fuzzy set that semantically represents the concept associated with the rule. To have a smooth and 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.

2.3. Defuzzification:

The fuzzy set that it describes the controller output in linguistic rules has to be converted into a feasible solution variable before it can be used to control the system. This is achieved by using a defuzzification. Various methods of defuzzification are available. The most commonly 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 upon the control surface.

3. Implementation of Fuzzy Pi Controller:

In this paper an adaptive fuzzy PI controller is used for damping oscillations in one machine, connected to network.Fig.5.
The conventional PI controller is given by:

$$u(t) = k_p[e(t) + \frac{1}{T}\int e(t)dt] \tag{1}$$

where k_p , T, and *e(t)* are the proportional gain, integral time and error respectively. Therefore transfer function of the equation (1) is:

$$Fu(s) = \frac{U(s)}{E(s)} = k_p + \frac{k_i}{s} \tag{2}$$

where k_p and k_i are the proportional gain and the integral gain of PI controller. These gains have been tuned by the fuzzy system in real time. Assume that the inputs to the fuzzy system are *e(t)* and/or *e'(t).* so the fuzzy system tuner consists of dual two-input one-output fuzzy systems as shown in Fig.1.

The three types of fuzzy system algorithms are presented in this paper: 3.1) a single input-single output control scheme, 3.2) another single input-single output control scheme and 3.3) two input-single output control scheme.

3.1. Single Input-single Output Control Scheme (Type 1):

In the type (1) controller, the time derivative of rotor speed of generator ώ is chosen as input and output of the fuzzy PI controller is used as a supplementary stabilizing signal, instead of PSS, to a digital AVR of the tested generator. The accelerating control of the study system is obtained by applying a positive stabilizing control signal to the excitation loop, while the decelerating control is obtained by applying a negative stabilizing control signal 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 control applied is negative" and "if the speed derivative is positive, then the control applied is positive". Thus at least two rules are needed. To realize a more efficient control, a set of seven rules are settled in this study as follows where PL (positive large), PM (positive medium), PS(positive small), ZE(zero), NS(negative small) , NM(negative medium) and NL(negative large). For each of these fuzzy sets, triangular membership function (MF) has been used. The membership function of ώ for tuning Kp is shown in Fig.2. Also the membership function of output for tuning Kp and the membership function of ώ and output for tuning Ki in the range of [-0.035 0.035], [-0.3 0.3] and [-1.5 1.5] respectively.

Rule 1: if ώ is NL then U is NL.
Rule 2: if ώ is NM then U is NM.
Rule 3: if ώ is NS then U is NS.
Rule 4: if ώ is ZR then U is ZR.
Rule 5: if ώ is PS then U is PS.
Rule 6: if ώ is PM then U is PM.
Rule 7: if ώ is PL then U is PL.

3.2. Single Input-single Output Control Scheme (Type 2):

In the type (2) controller, the acceleration of generator speed *d ώ* is chosen as input and signal U is the output of the fuzzy controller that tuned the K_p and K_i in the PI controller. Seven fuzzy subsets have been used in this scheme 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. Four membership functions have been used in this scheme similar type (1) controller. The membership function of ώ and output for tuning Kp and the membership function of ώ and output for tuning Ki in the range of [-1. 3 1. 3], [-1 1] , [-0.07 0.07] and [-0.15 0.15] respectively.

Rule 1: if *d ώ* is NL then U is NL.
Rule 2: if *d ώ* is NM then U is NM.
Rule 3: if *d ώ* is NS then U is NS.
Rule 4: if *d ώ* is ZR then U is ZR.
Rule 5: if *d ώ* is PS then U is PS.
Rule 6: if *d ώ* is PM then U is PM.
Rule 7: if *d ώ* is PL then U is PL.

3.3. Two Input- Single Output Control Scheme (Type 3):

In the type (3) controller, the acceleration of generator speed (*d ώ*) and the rotor speed deviation (*d ώ*) are selected as inputs and signal U is the output of the fuzzy controller. The parameters of the controller should be determined by trial and error using the simulation of system. Seven fuzzy subsets have been used in this scheme similar type (1). For each of these fuzzy sets, Gaussian membership function (MF) has been used. The membership function of *dώ* for tuning Kp is shown in Fig.3. Also the membership function of $d\omega$ and output for tuning Kp and the membership function of *dώ,* ώ and output for tuning Ki in the range of [-0.4 0.4], [-0.03 0.03], [-0.1 0.1], [-0.4 0.4], and [-0.03 0.3] respectively. Fuzzy subsets results through these fuzzy subsets for computing the output is shown in table 1.

4. 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.5. The basic parameters of the generator are shown in the appendix. The generator is equipped with an AVR and PSS.

5. Simulation Results:

To show the design process as well as to investigate the effectiveness of the fuzzy PI controllers, we set the three phase short circuit faults during [0.5 0.57] of time for two cases, namely AVR with PSS and AVR with Fuzzy PI Controller.

5.1. 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.4.

Fig.6 illustrates the dynamic behaviors of the generator for a three phase short circuit faults in the case of AVR and PSS in the one-machine connected to the network. The following variables are plotted: electrical output power (Pe) and rotor speed deviation (dω). The oscillations of the variables decay very slowly.

5.2. System Responses under Avr and Fuzzy Pi Controller:

Fig.7 shows the dynamic behaviors of the system under the type (1) fuzzy controller and AVR. From this figure, 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 with AVR are shown in Figs. 8,9.

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 PI 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.

The priority of the proposed controller can be explained as follows:

a) It follows a smooth gain scheduling design algorithm where a different controller is actually utilized according to the need of the plant.
b) Fuzzy controllers are nonlinear mappings while the CPSS is linear one. This nonlinearity donates more flexibility in shaping the control surface and providing better performance.
c) It 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.
d) Classical controllers such as CPSS, have demonstrated not to be efficient enough under practical tests because of the optimization procedure used to setup their parameters.

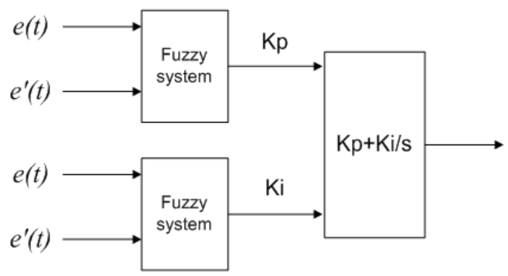


Fig. 1: Block diagram of the fuzzy-PI controller.

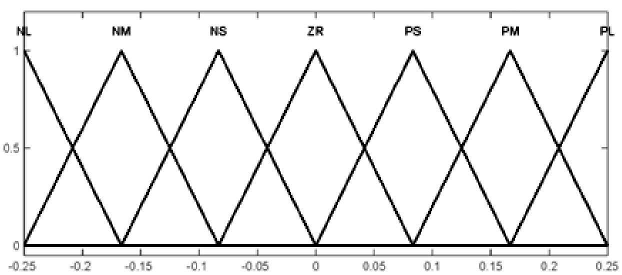


Fig. 2: Membership Function of ? for tuning Kp in type (1) fuzzy controller.

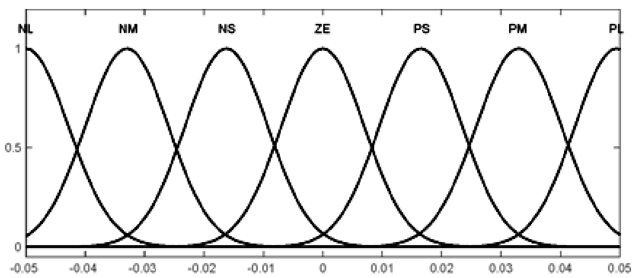


Fig. 3: Membership Function of *d ώ* for tuning Kp in type (3) fuzzy controller.

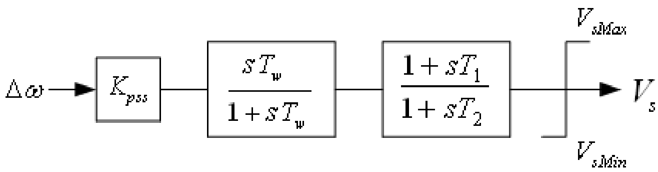


Fig. 4: Block diagram of the PSS.

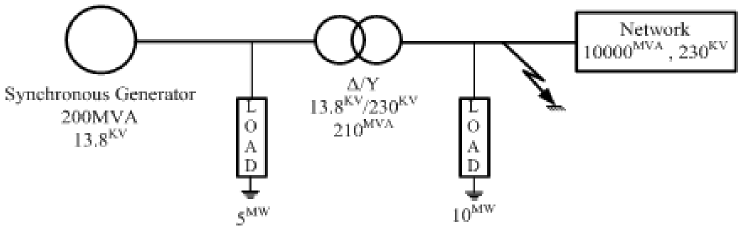


Fig. 5: The model of system.

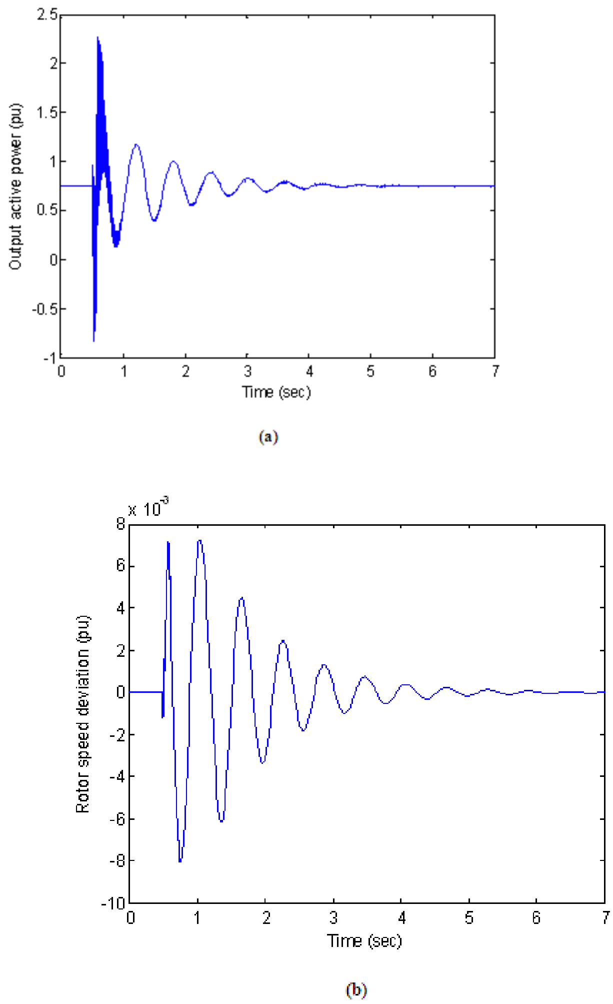
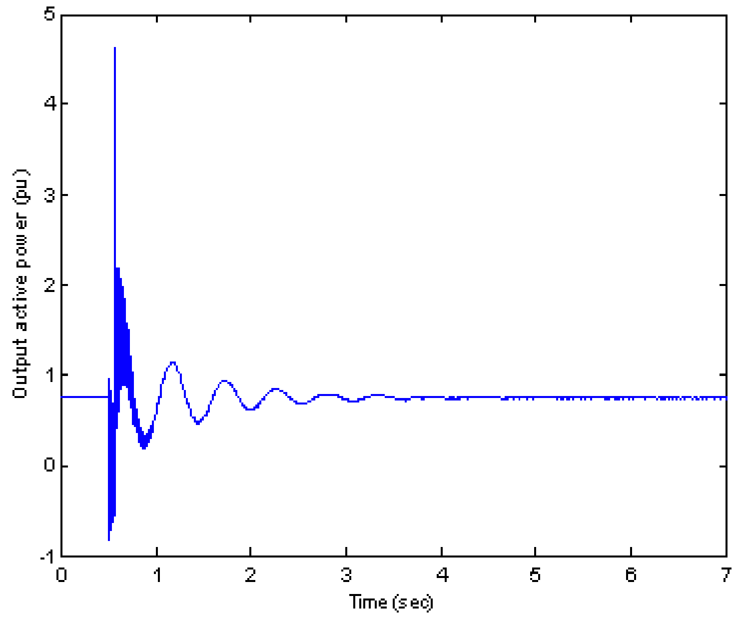
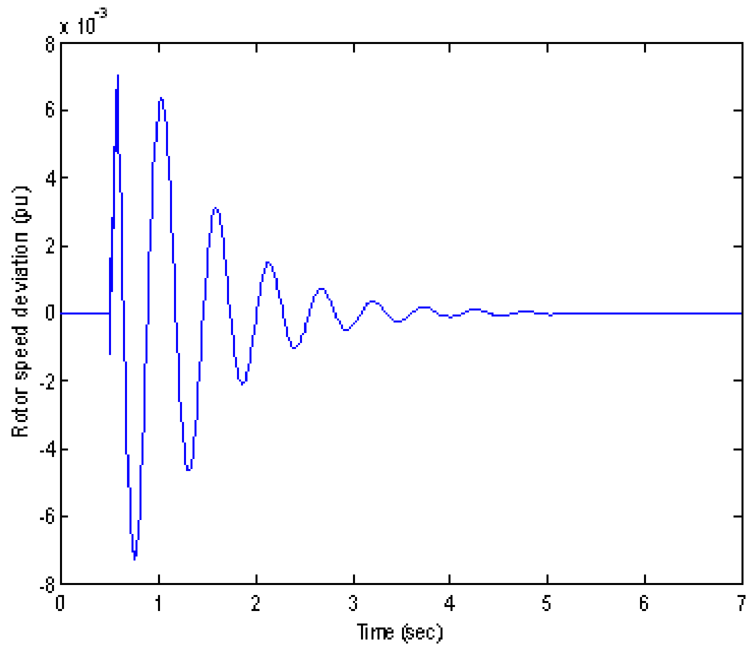


Fig.6: System responses under AVR and PSS.
(a): Output active power.
(b): Rotor speed deviation .

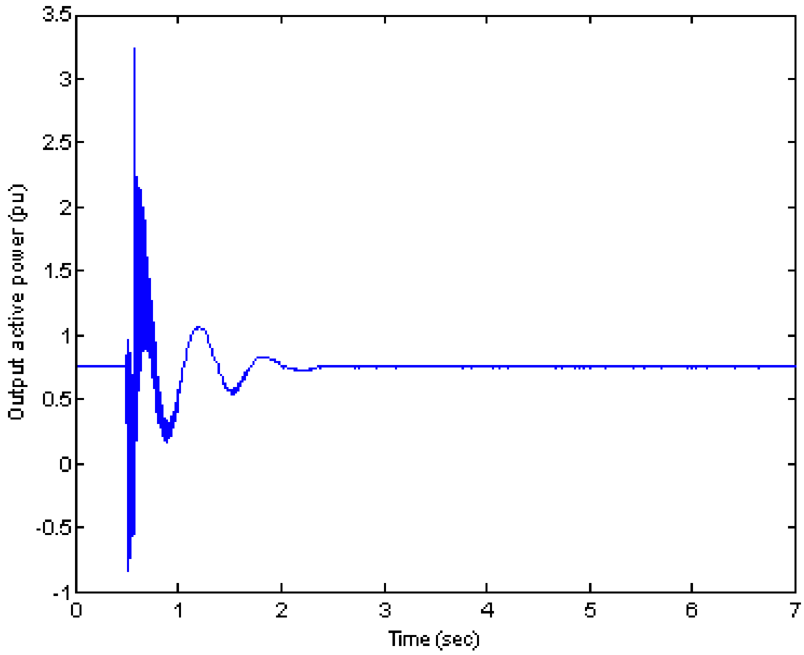


(a)

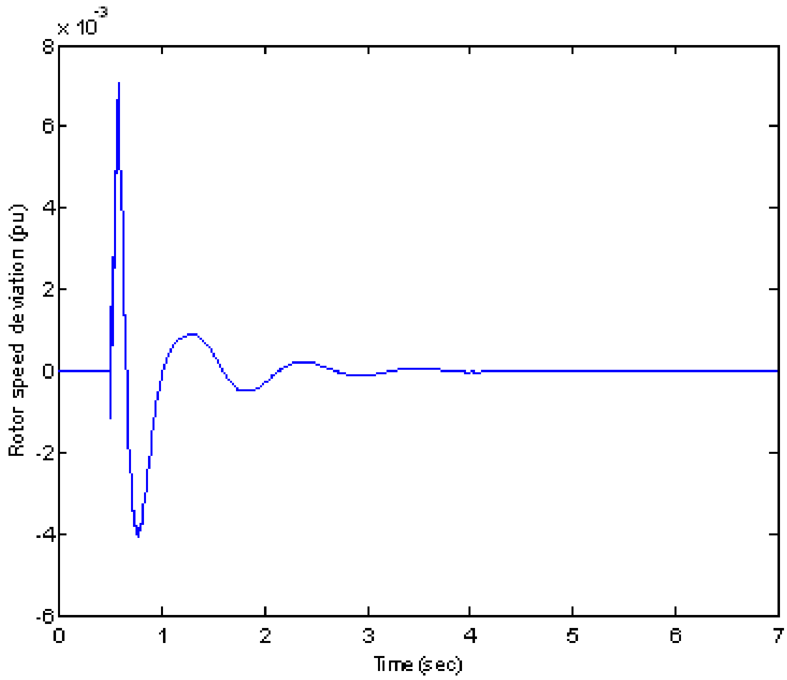


(b)

Fig.7: System responses under AVR and type (1) fuzzy controller.
(a): Output active power.
(b): Rotor speed deviation.



(a)



(b)

Fig. 8: System responses under AVR and type (2) fuzzy controller.
(a): Output active power.
(b): Rotor speed deviation.

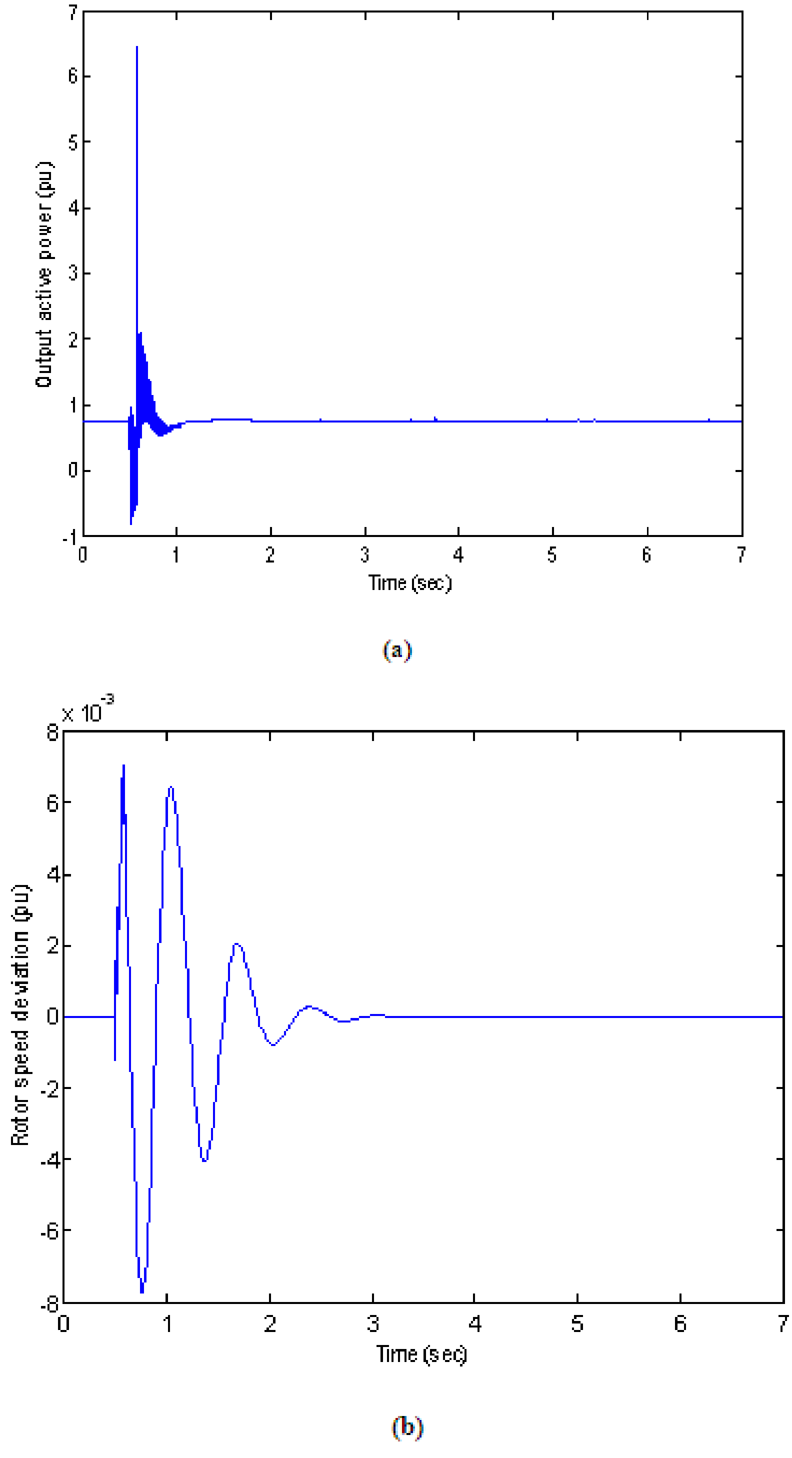


Fig. 9: System responses under AVR and type (3) fuzzy controller.
(a): Output active power
(b): Rotor speed deviation

Table1: fuzzy control rules.

dω / dώ	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PS	PS	PM	PB	PB	PB

Conclusions:

In this paper, the control performances of the three proposed fuzzy PI controllers, instead of PSS, under various operating conditions are investigated. The proposed controller provides a supplementary signal to the excitation system of the synchronous generator. The obtained results show that the proposed controller for stabilizing power system can provide very good damping characteristic.

This controller utilizes a combination of a FLC and a PI controller. In addition the proposed controller is simple to be implemented in real-time. In comparison with the conventional fuzzy controllers, the fuzzy PI controller incorporates the advantages of a FLC and a conventional PI controller. The design of the fuzzy PI 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 PI 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 are as follows:

$x_d = 1.305$ $\quad$ $x_l = 0.18$ $\quad$ $T'_d = 1.01$

$x''_d = 0.252$ $\quad$ $R_s = 2.85 \times 10^{-3}$ $\quad$ $T''_{q0} = 0.1$

$x_q = 0.474$ $\quad$ $H = 3.2$

PSS data:

$K_{pss} = 100$ $\quad$ $T_W = 1.41$ $\quad$ $T_1 = 0.154$

$T_2 = 0.033$ $\quad$ $V_{SMax} = 0.2$ $\quad$ $V_{SMin} = -0.2$