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ANFIS Approach Applied to PSS and SSSC Controllers for Power System Damping Improvement

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ABSTRACT: The transmission line transfer capability and power system stability are greatly affected by the low frequency electromechanical oscillations. The conventional approach to damp these oscillations is by the use of Power System Stabilizers (PSSs). However, the capability of Flexible AC Transmission System (FACTS) controllers, such as Static Synchronous Series Compensators (SSSCs) and Unified Power Flow Controllers (UPFCs), has been explored and proven. This paper investigates and compares the dynamic performance of conventional and Adaptive Neuro-Fuzzy Inference System (ANFIS) based PSS and SSSC controllers applied in a two-area power system. The time domain simulation results, carried out in Matlab / Simulink platform, of the two-area power system subjected to different operating conditions, validate the efficiency of the proposed robust and simple approach with very good dynamic responses. The results demonstrate that the ANFIS based SSSC controllers show good damping performance characteristics in terms of both reduced amplitudes and settling times of oscillations compared to ANFIS based PSS controllers.

KEYWORDS: ANFIS, Damping performance, FACTS, Low frequency oscillations, Matlab / Simulink, PSS, SSSC, Two-area power system, UPFC.

1 INTRODUCTION

In the 1950s and 1960s, electric power utilities found that they could achieve more reliability and economy by interconnecting to other utilities, often through quite long transmission lines. In some cases, when the utilities connected, low frequency growing oscillations prevented the interconnection from being retained [1, 2]. These oscillations were at frequencies of the order of 1 to 2 Hz as soon as synchronous generators were interconnected. If not well damped, these oscillations may keep growing in magnitude until loss of synchronism results [3]. Damper windings on the generator rotor were used to absorb the energy associated with the system oscillations and so cause their amplitudes to reduce. The oscillations may be local to a single generator or generator plant (local oscillations), or they may involve a number of generators widely separated geographically (inter-area oscillations). Local oscillations often occur when a fast exciter is used on the generator, and to stabilize these oscillations, Power System Stabilizers (PSSs) were developed. Inter-area oscillations may appear as the system loading is increased across the weak transmission links in the system which characterizes these oscillations. The oscillations of generator angle or line angle are generally associated with transmission system disturbances and can occur due to step changes in load, sudden change of generator output, transmission line switching, and short circuits. It is important to damp these oscillations as quickly as possible because they may cause mechanical wear in power plants and many power quality problems. The system is also vulnerable if further disturbances occur. If not controlled, these oscillations may lead to total or partial power interruption.

Some authors' work emphasized the enhancement of overall system stability and considered the simultaneous damping of inter-area and local modes, and discussed the performance of the PSS under different system conditions [4]. An approach was presented for designing fuzzy logic based adaptive power system stabilizers (PSS) for multi-machine power systems [5]. It is based on the traditional frequency domain method. In addition, a fuzzy signal synthesizer is introduced to achieve adaptiveness. In this approach, two linear stabilizers are designed to accommodate two extreme loading cases. A fuzzy logic mechanism is used to generate one single control signal by properly combining the outputs of the linear stablizers. The fuzzy controller is optimized using a least squares error criterion. Simulation studies of a one-machine infinite-bus and two multi-machine systems show that the proposed stabilizer provides satisfactory damping against low frequency oscillations under different operating conditions.

Some authors proposed a fuzzy-logic-based adaptive power system stabilizer whose parameters were tuned by neural networks online [6]. In this paper, the system was divided into two subsystems, a recursive least square identifier with a variable forgetting factor for the generator and a fuzzy-logic-based adaptive controller to damp oscillations. The effectiveness of the proposed PSS in increasing the damping of local and inter-area modes of oscillation was demonstrated on a one-machine-infinite-bus system and a two-area system. Some authors explained about PSS and control of reactive power compensator in multi-machine system by using particle swarm optimization algorithm [7]. Various approaches were also proposed to design damping controllers for different Flexible AC Transmission System (FACTS) devices. Some authors presented a novel methodology for tuning STATCOM based damping controller in order to enhance the damping of system low frequency oscillations. The design of STATCOM parameters are considered an optimization problem according to the time domain-based objective function solved by a Honey Bee Mating Optimization (HBMO) algorithm that has a strong ability to find the most optimistic results [8]. The control strategy of a SSSC was derived using optimal control design. The simulation results were tested on a Single Machine Infinite Bus system (SMIB) [9]. The proposed method was equipped in a sample system with disturbance. The generator rotor angle curve of the system without and with a SSSC was plotted and compared. It was found that the system without a SSSC has high variation whereas that of the system with a SSSC has much smaller variation. Some authors proposed an Adaptive Network-based Fuzzy Inference System controller (ANFISC) for controlling of the SSSC-based damping system applied in a SMIB power system. For implementation of the learning process of this controller, an approach of the learning ability that was named as Forward Signal and Backward Error Back-Propagation (FSBEBP) method for improving the system efficiency was used [10].

From the above literature reviews, it is evident that there are many devices (PSS and various FACTS devices) that can help the damping of power system oscillations, and there are also many different control methods for the damping controller design. The objective of this paper is to design advanced PSS and SSSC controllers to enhance damping of power system oscillations. This work is an attempt to illustrate the utility and effectiveness of intelligent control strategies for the design of both PSS and SSSC controllers. The intelligent control approach is concerned with the integration of artificial intelligent tools (neural networks, fuzzy technology, evolutionary algorithms, etc) in a complementary hybrid framework for solving real world problems. There are several approaches to integrate neural networks and fuzzy logic to form a neuro-fuzzy system. The present work will concentrate on the damping improvement by (i). Conventional PSS and SSSC controllers applied in a two-area power system, and (ii). ANFIS based PSS and SSSC controllers applied in the same two-area power system.

The structure of the work presented in this paper is organized in the following sequence. A brief review of the literature survey of the related work has been presented in the previous paragraphs in the introductory section. Section 2 presents the model of a two-area power system. The architecture of the adaptive neuro-fuzzy inference scheme used in the design of the controller for PSS / SSSC is presented in Section 3. The design of the ANFIS controller is illustrated in Section 4. The simulation results and discussions are presented in Section 5. This is followed by the conclusions in the concluding section 6.

2 POWER SYSTEM MODEL

A three-machine nine-bus power system shown in Fig. 1 in the form of single line diagram is used to investigate inter-area oscillation control problem [11]. In this system, the bus 1 is taken as reference bus. The system frequency is 50 Hz and the base power is 100 MVA. The frequency of inter-area mode electromechanical oscillations of this system may range from 0.35 to 0.75 Hz depending on the operating conditions. To analyze the damping performance of the system, initially two-sets of conventional lead-lag PSS controllers are employed; one for the generator G2 (Area 1) and another one for the generator G3 (Area 2) respectively. Next, two-sets of conventional SSSC based damping controllers are installed in the system; one between bus 5 and bus 7, and another one between bus 6 and bus 9 respectively. The details of system data are given in Figure 1. The G2 has Rated MVA = 192, Rated voltage = 18 kV. The G3 has Rated MVA = 128, Rated voltage = 13.8 kV. The reduced Y-bus matrix for the three-bus power system is as shown below:

$$[Y_{Bus}] = \begin{bmatrix} 0.846 - j2.988 & 0.287 + j1.513 & 0.210 + j1.226 \\ 0.287 + j1.513 & 0.420 - j2.724 & 0.213 + j1.088 \\ 0.210 + j1.226 & 0.213 + j1.088 & 0.277 - j2.368 \end{bmatrix}$$

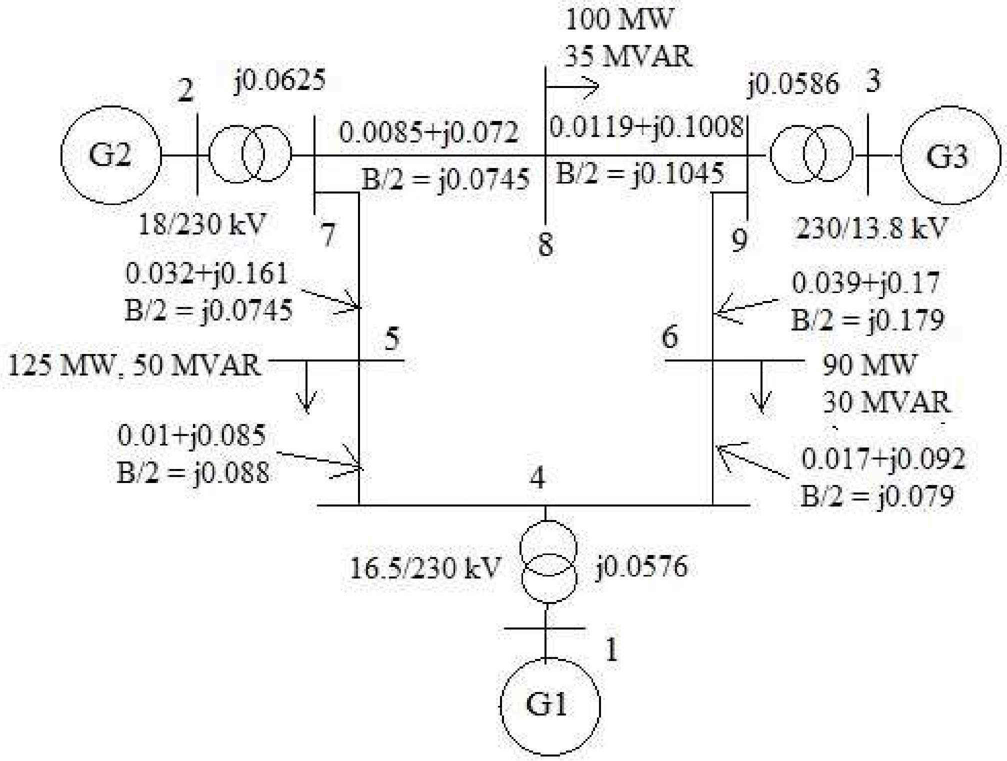

Fig. 1. Single line diagram of a Three-machine nine-bus power system

3 ADAPTIVE NEURO-FUZZY INFERENCE SCHEME

The FIS (Fuzzy Inference System) is a popular computing framework based on the concepts of fuzzy set theory, fuzzy if-then rules, and fuzzy reasoning [12, 13]. The ANFIS is a class of adaptive networks which are functionally equivalent to FISs. The selection of the FIS is the major concern in the design of an ANFIS. In this paper, the first-order Sugeno fuzzy model is used to generate fuzzy rules from a set of input-output data pairs [14]. Among many FIS models, the Sugeno fuzzy model is the most widely applied one for its high interpretability and computational efficiency, and built-in optimal and adaptive techniques. A typical architecture of ANFIS is depicted in Fig. 2, in which a circle indicates a fixed node, whereas a square indicates an adaptive node. For simplicity, it is assumed that the FIS has two inputs x and y and one output z. The structure of the network is composed of a set of units (and connections) arranged into five connected network layers which are described as shown below:

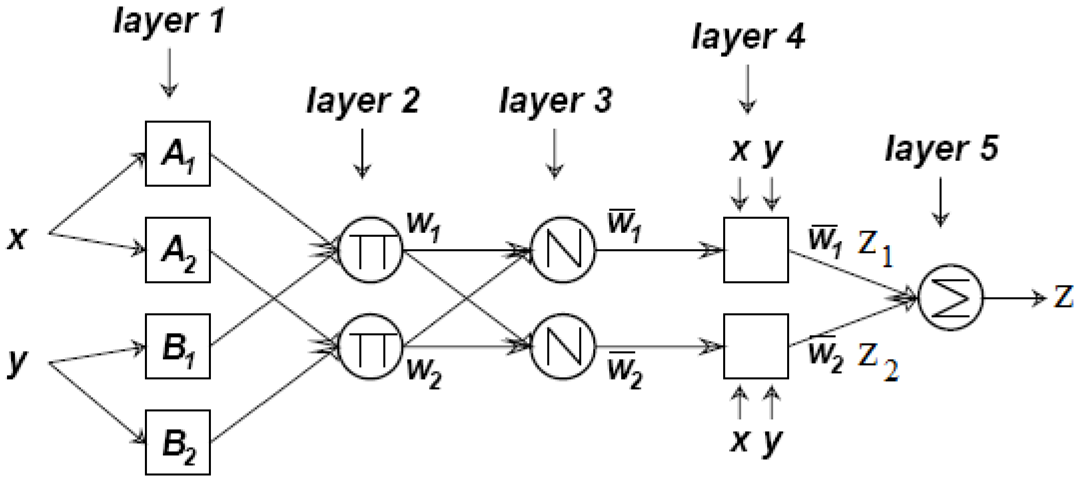

Fig. 2. A typical architecture of ANFIS

Layer 1: Every node i in this layer is a square node with node function

$$O_{1,i} = \mu_{A_i}(x) \quad \text{for } i = 1, 2 \tag{1}$$

where, x is the input to node i, and A_i is the linguistic label (small, large, etc.) associated with this node function. Usually, $\mu_{A_i}(x)$ is given by

$$\mu_{A_i}(x) = \frac{1}{1+\left[\left(\frac{x-c_i}{a_i}\right)^2\right]^{b_i}} \tag{2}$$

where, $\{a_i, b_i, c_i\}$ is the parameter set. Parameters in this layer are referred to as premise parameters.

Layer 2: Every node in this layer is a circle node labeled $\prod$ (product) which multiplies the incoming signals and sends the product out. For instance,

$$w_i = \mu_{A_i}(x) \times \mu_{B_i}(y) \quad \text{for } i = 1, 2 \tag{3}$$

Every node output represents the firing strength of a rule.

Layer 3: Every node in this layer is a circle node labeled N. The ith node calculates the ratio of the ith rule's firing strength to the sum of all rules' firing strengths.

$$\vec{w}_i = \frac{w_i}{w_1 + w_2} \quad \text{for } i = 1, 2 \tag{4}$$

where $\vec{w}_i$ is referred to as the normalized firing strengths.

Layer 4: Every node i in this layer is a square node with a node function The nodes of the fourth layer are adaptive nodes, each with a node function

$$O_{4,i} = \vec{w}_i z_i = \vec{w}_i (p_i x + q_i y + r_i) \tag{5}$$

where $\vec{w}_i$ is the output of layer 3, and $\{p_i, q_i, r_i\}$ is the parameter set. Parameters in this layer are referred to as consequent parameters.

Layer 5: The single node in this layer is a circle node labeled $\sum$ that computes the overall output as the summation of all incoming signals, i.e.,

$$\text{Overall output} = O_{5,i} = \sum_i \vec{w}_i z_i = \frac{\sum_i w_i z_i}{\sum_i w_i} \quad \text{for } i = 1, 2 \tag{6}$$

The least square estimation and back propagation algorithm are employed to tune the ANFIS structure automatically. The algorithm shown above is used in the next section to develop the ANFIS controllers for PSS (and SSSC) to damp out the oscillations in a two-area power system. Because of its flexibility, the ANFIS strategy can be used for a wide range of control applications.

4 ANFIS CONTROLLER

In this section, the closed loop configuration of ANFIS control scheme for PSS (and SSSC) controllers for damping oscillations in the two-area power system is presented and discussed. The closed loop block diagram of the system is shown in Fig. 3. The controller is designed using the ANFIS scheme. Fuzzy logic is one of the successful applications of fuzzy set in which the variables are linguistic rather than the numeric variables. The linguistic variables may be represented by the fuzzy sets. Fuzzy set is an extension of a 'crisp' set where an element can only belong to a set (full membership) or not belong at all (no membership).

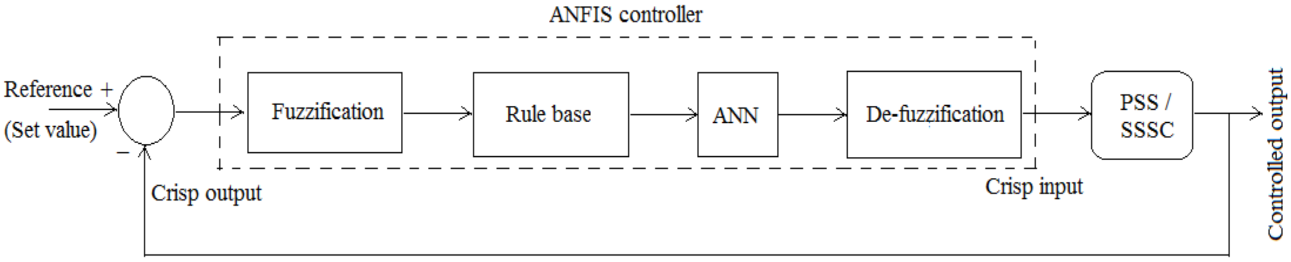

Fig. 3. Closed loop block diagram showing ANFIS control scheme for PSS / SSSC controllers

The fuzzy rules are expressed in the form of conditional statements. The four important parts of the developed ANFIS coordination controller for PSS (and SSSC) are fuzzification, knowledge base (rule base), artificial neural network (ANN) and the de-fuzzification blocks respectively, which are explained in brief in the following paragraphs.

The inputs to the ANFIS controller, i.e., the error and the change in error are modeled using the Eqn. (7).

$$e(k) = \omega_{ref} - \omega_r \qquad \Delta e(k) = e(k) - e(k-1) \tag{7}$$

where ω_{ref} is the reference speed, ω_r is the actual rotor speed, $e(k)$ is the error, and $\Delta e(k)$ is the change in error.

The crisp data are converted into linguistic variables by the fuzzification unit. The set of 49 rules is written on the basis of previous knowledge/experiences in the rule based block and is included in the ANFIS controller. The control decisions are made based on the fuzzified variables as shown in Table 1. The rule base block is connected to the neural network block. Back propagation algorithm is used to train the Artificial Neural Network (ANN) to select the proper set of rule base. Once the proper rules are selected and fired, the control signal required to obtain the optimal outputs is generated. The output of the ANN unit is given as input to the de-fuzzification unit and the linguistic variables are converted back into the numeric form of data in the crisp form In the fuzzification process, i.e., in the first stage, the crisp variables, the speed error and the change in error are converted into fuzzy variables or the linguistics variables. The fuzzification maps the two input variables to linguistic labels of the fuzzy sets. The fuzzy coordinated controller uses the linguistic labels. Each fuzzy label has an associated membership function. The membership function of Gaussian type used in our work is shown in Fig. 4. The defuzzifcation transforms fuzzy set information into numeric data information. There are so many methods to perform the defuzzifcation, viz., centre of gravity method, centre of singleton method, maximum methods, and the marginal properties of the centroid methods and so on. In our work, we use the centre of gravity method. The output of the defuzzification unit will generate the control commands which in turn is given as input (called as the crisp input) to the PSS (or SSSC) controller. If there is any deviation in the controlled output (crisp output), this is fed back and compared with the set value, and the error signal is generated which is given as input to the ANFIS controller which in turn brings back the output to the normal value, thus maintaining stability in the system. Finally, the controlled output is the weighted average of the proper rule based outputs, which are selected by the back propagation algorithm.

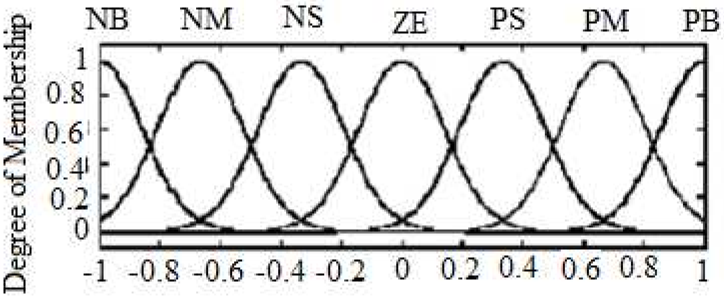

Fig. 4. Gaussian membership functions

Table 1. Rules extracted from the conventional PSS (or SSSC) controller

Speed Deviation	**Acceleration**						
	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NM	NM	NS	ZE	ZE	PM	PM
PS	NM	NS	ZE	ZE	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	ZE	PM	PS	PB	PB	PB

5 TIME DOMAIN SIMULATION RESULTS AND DISCUSSION

The proposed robust ANFIS control scheme is applied to PSS and SSSC controllers in the two-area power system shown in Fig. 1. Each machine of this power system is represented by a fourth order two-axis nonlinear model. The details of system data are indicated in the single line diagram [15, 16]. The per unit inertia constants (M) of generator G2 and G3 are considered as 6.0 and 3.01 respectively. The damping performance characteristics of ANFIS based PSS and SSSC controllers have been examined under two different operating conditions: (i). Total real power of load P=0.75 p.u, Total reactive power of load Q=0.85 p.u, Terminal voltage V_t = 1.05 p.u, Torque disturbance ΔT_m = 0.006 p.u, Disturbance clearing time = 50 sec.. (ii). Total real power of load P=0.85 p.u, Total reactive power of load Q=0.95 p.u, Terminal voltage V_t =1.05 p.u, Torque disturbance ΔT_m = 0.006 p.u, Disturbance clearing time = 50 sec. In this paper, the first set of operating point is considered for illustration.

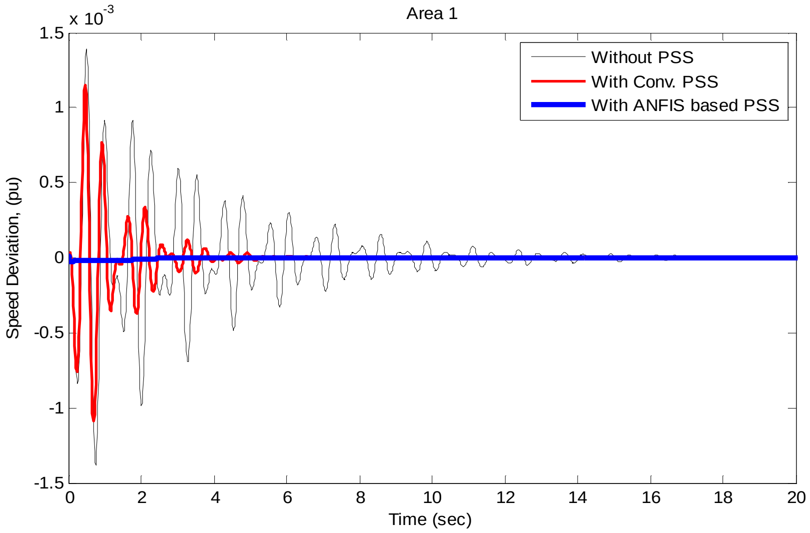

Fig. 5. Variation of Generator 2 (G2) Speed deviation with time for Torque disturbance ΔT_m = 0.006 p.u with ANFIS based PSS (P = 0.75 p.u, Q = 0.85 p.u)

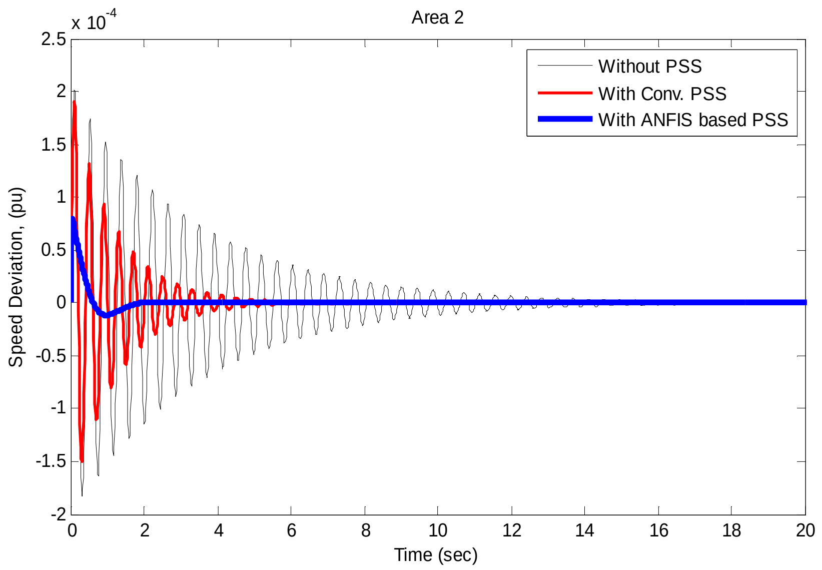

Fig. 6. Variation of Generator 3 (G3) Speed deviation with time for Torque disturbance $\Delta T_m = 0.006$ p.u with ANFIS based PSS (P = 0.75 p.u, Q = 0.85 p.u)

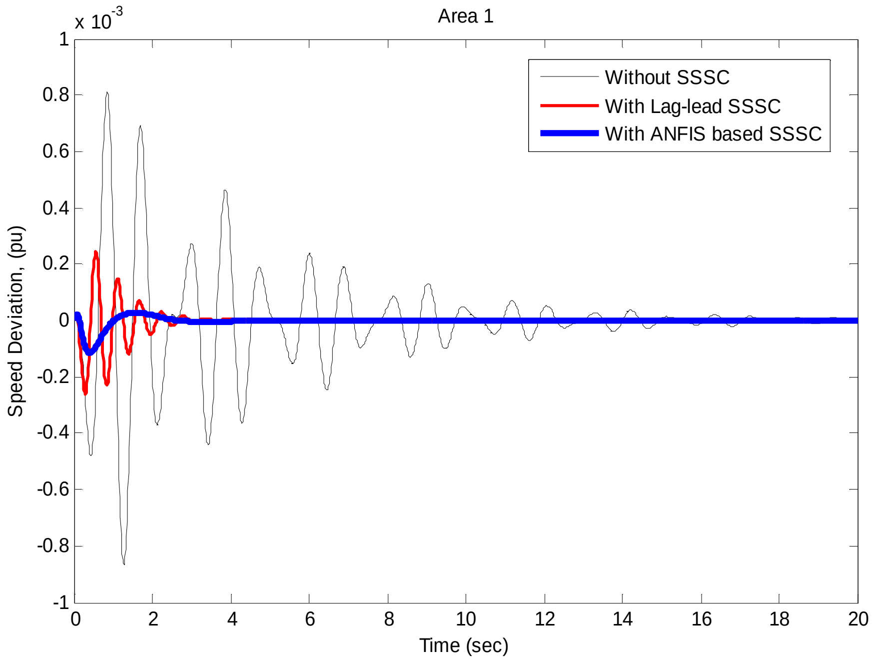

Fig. 7. Variation of Generator 2 (G2) Speed deviation with time for Torque disturbance $\Delta T_m = 0.006$ p.u with ANFIS based SSSC (P = 0.75 p.u, Q = 0.85 p.u)

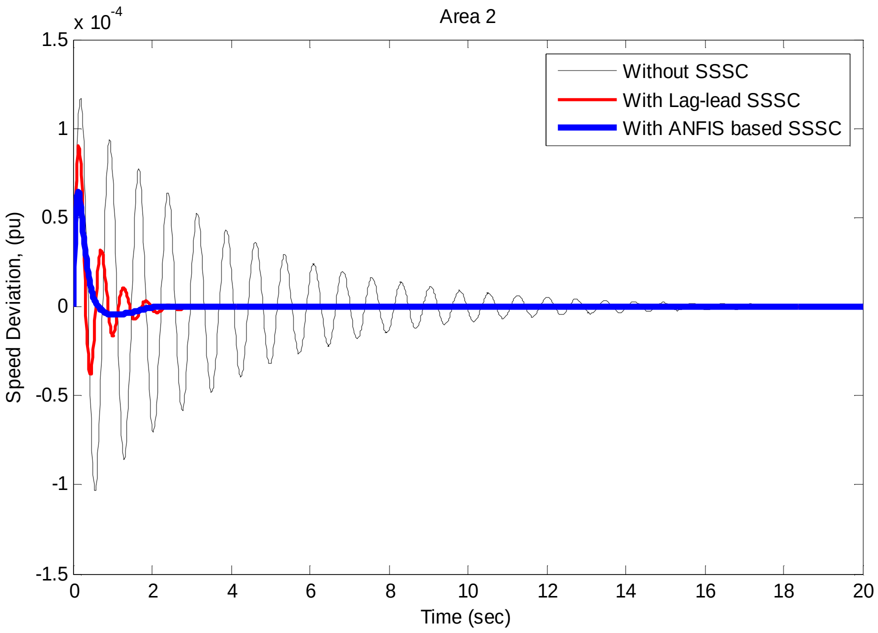

Fig. 8. Variation of Generator 3 (G3) Speed deviation with time for Torque disturbance $\Delta T_m = 0.006$ p.u with ANFIS based SSSC (P = 0.75 p.u, Q = 0.85 p.u)

Initially, the damping performance of the two-area power system was analyzed without PSS or SSSC controllers and it was shown to be very poor in terms of increased amplitudes and settling times of oscillations as shown in Figs. 5-8 [17]. To improve the damping performance of the system, initially conventional lead-lag PSS controllers are introduced in the system. Then the conventional PSS controllers are coordinated through ANFIS control scheme to have further improvement in damping of oscillations. From the Figs. 5 and 6, it is inferred that the ANFIS based PSS controllers show good damping performance compared to conventional PSS controllers. Next, the system is installed with conventional SSSC based damping controllers which show improved damping performance compared to conventional PSS controllers as is seen from the Figs. 7 and 8. Then the ANFIS control approach is employed to conventional SSSC controllers to have still improved damping characteristics. Thus, it is understood from the Figs. 5-8 that the ANFIS based SSSC controllers can provide better damping of speed deviation (and hence power angle oscillations) of Area 1 and Area 2 of the two-area power system in terms of somewhat reduced amplitudes and settling times, compared to ANFIS based PSS control scheme.

6 CONCLUSION

In this work, the power system damping enhancement via PSS and SSSC based damping controllers when applied independently has been discussed and investigated. The efficiency and robustness of the proposed ANFIS control approach are evaluated on a two-area power system with PSS and SSSC based damping controllers installed. From the time domain simulation studies carried out in Matlab/Simulink environment separately for PSS and SSSC controllers, it is evident that the Adaptive Neuro-Fuzzy based SSSC controllers are capable to provide better and fast damping characteristics in the form of reduced overshoots of oscillations in speed deviation of Generators G2 and G3 of the two-area power system when compared to Adaptive Neuro-Fuzzy based PSS control scheme under different operating conditions.

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