DYNAMIC PERFORMANCE IMPROVEMENT OF A TWO-AREA POWER SYSTEM BY PSS AND SERIES FACTS BASED DAMPING CONTROLLERS USING ANFIS TECHNOLOGY

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Abstract – *The most common control action to enhance damping of the power system oscillations is provided by the use of Power System Stabilizers (PSSs). The function of this device is to extend stability limits by modulating generator excitation to provide damping to the electromechanical oscillations. Nowadays, due to the technological stage of high power electronic devices, other effective solution such as the use of FACTS (Flexible AC Transmission System) controllers to damp low frequency electromechanical oscillations is being considered. Here, the series FACTS based damping controller such as Static Synchronous Series Compensator (SSSC) is employed. In this paper, an adaptive damping controller using ANFIS (Adaptive Neuro-Fuzzy Inference System) approach has been proposed to provide a robust and flexible power oscillation damping performance for both PSS and SSSC devices applied in a two-area power system. The efficiency of the proposed approach is validated through simulation, carried out in Matlab/Simulink environment. The digital simulation results have shown that even though initial overshoot may be slightly high, there is a significant reduction in settling time for the system with neuro-fuzzy based SSSC controller when subjected to small-signal perturbations, as compared with neuro-fuzzy based PSS control scheme.*

Keywords: ANFIS, Electromechanical oscillations, FACTS, PSS, SSSC, Two-area power system.

1. Introduction

The low frequency electromechanical oscillations that are caused by the interaction between the electrical transmission system and the mechanical system of the generators may be of local or inter-area type [1]-[3]. Power System Stabilizers (PSSs) were developed to stabilize the local oscillations. It is important to damp the inter-area oscillations as quickly as possible since they may cause mechanical wear in power plants and many power quality problems, and if not controlled, these oscillations may lead to total or partial power interruption.

A single-machine infinite-bus (SMIB) system was used to analyze the nature of the low frequency electromechanical oscillations in power systems. The effectiveness of a speed-based PSS, to compensate the negative impact on damping torque caused by the excitation system, was demonstrated through analog simulation [4].

Hsu and Cheng [5] proposed a PSS based on fuzzy set theory. Speed deviation of a synchronous machine and its derivative were chosen as the input signals to the fuzzy stabilizer. A classical Mamdani type fuzzy system was used to build a mapping relationship from inputs to control output. A seven-by-seven rule table was employed, and all the membership functions were determined based on the authors' experience and no optimization on these membership functions was considered in their paper. The proposed PSS was tested on a two-machine nine-bus system including an infinite-bus. The results reported showed better damping as compared with a conventional lead-lag PSS.

Some papers [6, 7] were published on applying rule-based fuzzy logic controllers to stabilize power systems. The author used speed deviation and acceleration as two inputs and constructed a phase plane. The phase plane was divided into several sectors which represent different control regions and require different control actions. Most parameters used in this controller were represented in a linguistic form. A PSS with a fuzzy logic based parameter tuner was proposed by some authors [8]. Reduced order linear models for the synchronous generator at a large number of operating points were obtained and the optimal PSSs at each operating point were designed by the traditional frequency domain method. In addition, a fuzzy signal synthesizer was introduced to achieve adaptiveness based on the operating condition.

Various approaches were also proposed to design damping controllers for different FACTS devices. Some authors compared the performance of ANFIS based Static Synchronous Series Compensator (SSSC), Static Synchronous Compensator (STATCOM) and Unified Power Flow Controller (UPFC) devices for transient stability improvement [9]. Prachanon Kumkratug [10] proposed the control strategy of a SSSC to enlarge the stability region of a simple power system. The control was determined very carefully to satisfy the Lyapunov's stability criterion and was found to be a non-linear function of system states. The proposed nonlinear control of SSSC for damping power system oscillations was investigated through the sample system.

It can be seen from the above reviews that there are 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.

ii). Adaptive Neuro-Fuzzy Inference System (ANFIS) based PSS and SSSC controllers applied in the same two-area power system.

Heuristic rules are derived with the Gaussian membership functions of the fuzzy variables tuned by a neural network. The proposed ANFIS based PSS improved the damping of power system oscillations, comparing with the conventional lead-lag PSS. However, the proposed ANFIS based SSSC controllers showed improved damping performance with reduced settling times under various operating conditions and disturbances.

The structure of the research work presented in this paper is organized in the following sequence. A brief review of the literature survey of the related work was presented in the previous paragraphs in the introductory section. Section 2 presents the model of a two-area power system. The design aspects of conventional lead-lag PSS and SSSC controllers are given in Section 3, and the concept of ANFIS control scheme is also presented in Section 3. The simulation results and discussions are given in Section 4. This is followed by the conclusions in the concluding section 5 and the appendix.

2. Model of two-area power system

A two-area power system used to investigate inter-area oscillation control problem [11] is shown in Fig. 1 in the form of one line diagram. 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 G1 (Area 1) and another one for the generator G2 (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 [12, 13] are given in Appendix. The reduced Y_{Bus} matrix for the above system is given by

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

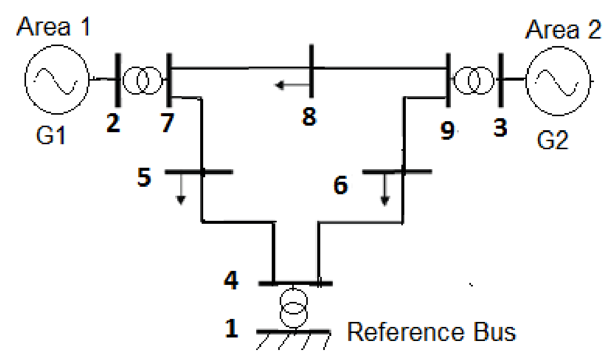

Fig. 1. One line diagram of a Two-area power system

3. Design aspects

In this section, the design concepts of conventional lead-lag PSS and SSSC based damping controllers, and the concepts of ANFIS control scheme are described.

3.1 Design of conventional lead-lag PSS controller

The PSS can provide damping to electromechanical oscillations by forcing the change in excitation level appropriately. The structure of conventional lead-lag PSS (CPSS) controller is shown in Fig. 2. It has three components; gain block, signal washout block and phase compensation block. The amount of damping introduced by PSS is determined by the gain K. The suitable value for K is taken as 400. In signal washout block serving as high pass filter, the washout time constant T_w is chosen to be a high value such that the signals associated with oscillations in ω are allowed to pass unchanged. In our work, the value of T_w is taken as 3 seconds. The compensation for the phase lag between exciter input and generator electrical torque is done by the phase compensation block which provides the appropriate phase lead characteristics. In this block, the time constants T_1 and T_2 are selected as 0.1537 and 0.1 seconds respectively. The outputs of washout and phase compensation blocks are given by Eqns. (1) and (2) respectively.

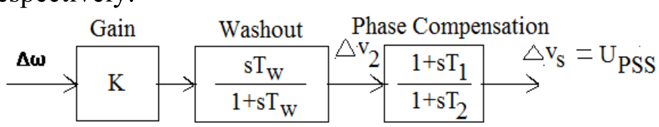

Fig. 2. Structure of conventional PSS

$$\Delta v_2 = \frac{sT_w}{(1+sT_w)}(K)(\Delta\omega) \qquad (1)$$

$$\Delta v_s = U_{PSS} = \frac{1+sT_1}{1+sT_2}(\Delta v_2) \qquad (2)$$

3.2 Design of conventional SSSC based damping controller

A damping controller is designed to improve the damping torque. The structure of an SSSC based damping controller [14] is shown in Fig. 3. It consists of gain, signal wash-out and phase compensator blocks. The block of signal wash-out is a high pass filter that modifies the SSSC input signal and prevents steady changes in active power. Therefore, T_w is assumed to be equal to 3 seconds and T_{a1} and T_{a2} are assumed to be 1.1 and 0.05 seconds respectively. The Saturation: Upper limit = 0.05, Lower limit = - 0.05.

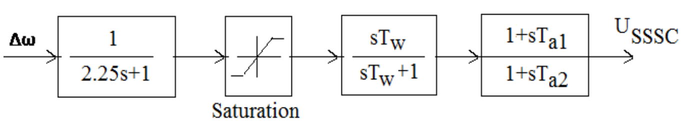

Fig. 3. Structure of SSSC based damping controller

3.3 ANFIS control scheme

The ANFIS makes use of a hybrid-learning rule to optimize the fuzzy system parameters of a first-order Sugeno system [15, 16]. The Sugeno fuzzy model (also known as Tsukamoto fuzzy model) is presented to save a systematic method to produce fuzzy rules of a certain input-output data set. The architecture of two inputs, two-rule first-order ANFIS Sugeno system is shown in Fig. 4. The system has only one output. The general ANFIS control structure contains the same components as the FIS (Fuzzy Inference System), except for the neural network block. 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:

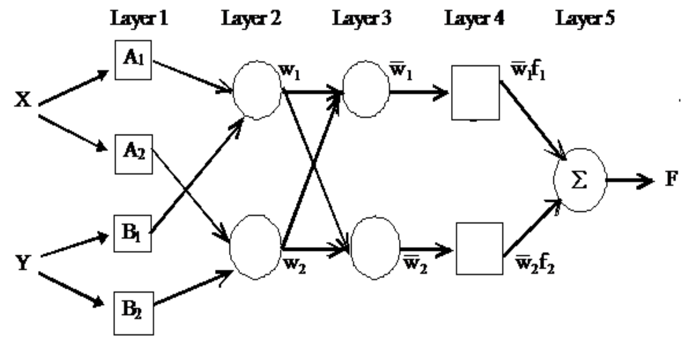

Fig. 4. An ANFIS architecture for a two-rule Sugeno system

The first layer of the ANFIS has adaptive nodes with each node having its function

$$O_{1,i} = \mu_A(x_1), \quad \text{for } i = 1, 2 \quad \text{or}$$

$$O_{1,i} = \mu_B(x_2), \quad \text{for } i = 3, 4 \qquad (3)$$

where, x_1 and x_2 are the inputs; and A_i and B_i are linguistic labels for the node. And $O_{1,i}$ is the membership grade of a fuzzy set $A(= A_1, A_2, B_1 \text{ or } B_2)$ to define the degree of applying the input to the set A. The second layer has fixed nodes, where its output is the product of the present signals to act as the firing power of a rule.

$$O_{2,i} = \mu_A(x_1)\mu_B(x_2), \quad i = 1, 2 \qquad (4)$$

The third layer also has fixed nodes; the i^{th} node computes the ratio of the i^{th} rule's firing strength to the rules' firing strengths sum:

$$O_{3,i} = \vec{w}_i = \frac{w_i}{w_1 + w_2}; \quad i = 1, 2 \qquad (5)$$

The nodes of the fourth layer are adaptive nodes, each with a node function

$$O_{4,i} = \vec{w}_i f_i = \vec{w}_i (p_i x_1 + q_i x_2 + r_i) \qquad (6)$$

where $\vec{w}_i$ is a normalized firing strength produced by layer 3; $\{p_i, q_i, r_i\}$ is the parameter set of the node, and pointed to consequent parameters. In our work, $x_1 = \Delta\omega$ (speed deviation error) and $x_2 = \Delta\dot{\omega}$ (acceleration).

$O_{4,i} = U_{PSS}$ or U_{SSSC}. There is a single node in the fifth layer, which is a fixed node, which calculates the resultant output as the summation of all signals.

$$\text{Overall output} = O_{5,i} = \sum_i \vec{w}_i f_i = \frac{\sum_i w_i f_i}{\sum_i w_i} \qquad (7)$$

The proposed ANFIS controller for PSS / SSSC uses seven linguistic variables such as: Positive Big (PB), Positive Medium (PM), Positive Small (PS), Zero (ZE), Negative Small (NS), Negative Medium (NM) and Negative Big (NB). Gaussian membership functions are chosen as shown in Fig. 5. The weighted average method is used to test the defuzzification of the variables into crisp outputs.

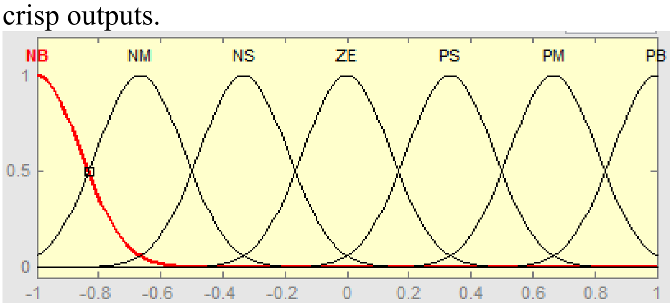

Fig. 5. Gaussian membership functions

Table 1 Rules extracted from the conventional PSS / SSSC controller

Speed Dev.	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

In Matlab/Simulink, the ANFIS editor graphics user interface is available in Fuzzy Logic Toolbox [17]. Using a given input/output data set, the toolbox constructs a fuzzy inference system (FIS), as shown in Table 1 above, whose membership function parameters are adjusted using either a backpropagation algorithm alone, or in combination with a least squares type of method. The input signals to the ANFIS controller for PSS / SSSC are $\Delta\omega$ and $\Delta\dot{\omega}$. In the ANFIS editor, the fuzzy inference can be generated using two partition methods such as grid partitioning and subtractive clustering. Here, grid partitioning method is used. For grid partitioning, it uses the Fuzzy C-means (FCM) clustering data clustering technique. FCM is a data clustering algorithm in which each data point belongs to a cluster with a degree specified by a membership grade. After generating the fuzzy inference, the generated information describing the model's structure and parameters of both the input and output variables are used in the ANFIS training phase. This information will be fine-tuned by applying the hybrid learning or the backpropagation schemes. The generated model is of a first-order Sugeno's form and the generated rules are in the form described in Eqn. (6).

4. Simulation results and discussion

To test the performance of the proposed robust ANFIS control scheme applied to PSS and SSSC controllers, the two-area power system shown in Fig. 1 is considered. Each machine of this power system is represented by a fourth order two-axis nonlinear model. The per unit inertia constants (M) of generator G1 and G2 are considered as 7.0 and 4.02 respectively. The block diagram for low frequency oscillation studies is shown in Fig. 6 [12]. This block diagram is simulated in Matlab/Simulink environment with PSS and SSSC controllers connected separately in the system.

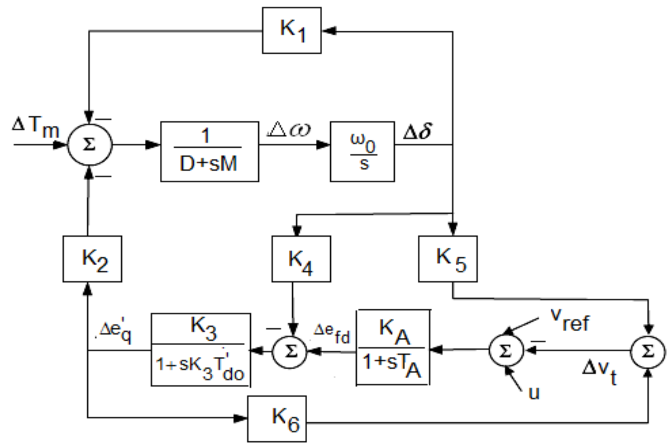

Fig. 6. Block diagram for low frequency oscillation studies

The damping performance characteristics of ANFIS based PSS and SSSC controllers are examined under two different operating conditions: (i). Total real power of load P=0.6 p.u, Total reactive power of load Q=0.7 p.u, Terminal voltage V_t =1.05 p.u, Torque disturbance ΔT_m = 0.004 p.u, Disturbance clearing time= 50 seconds. (ii). Total real power of load P=0.8 p.u, Total reactive power of load Q=0.9 p.u, Terminal voltage V_t=1.05 p.u, Torque disturbance ΔT_m= 0.004 p.u, Disturbance clearing time = 50 seconds. In this paper, the first set of operating point is considered for illustration.

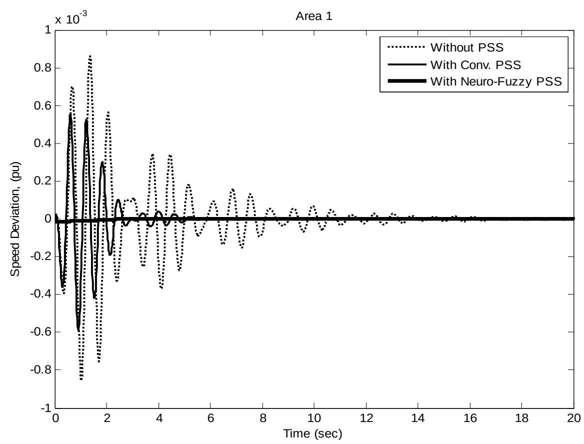

Fig. 7. Dynamic response of Speed deviation for ΔT_m = 0.004 p.u with Neuro-Fuzzy based PSS for Area 1 (P=0.6 p.u, Q=0.7 p.u)

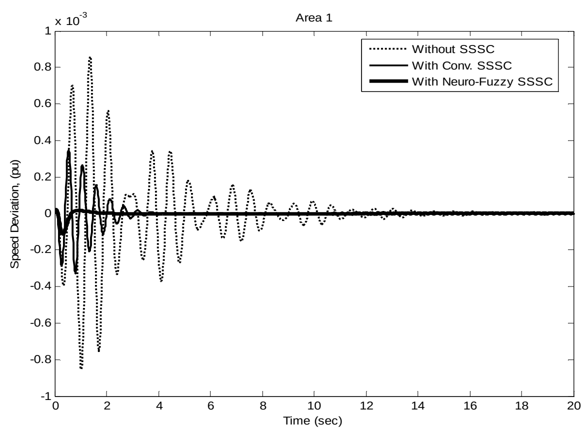

Fig. 8. Dynamic response of Speed deviation for ΔT_m = 0.004 p.u with Neuro-Fuzzy based SSSC controller for Area 1 (P=0.6 p.u, Q=0.7 p.u)

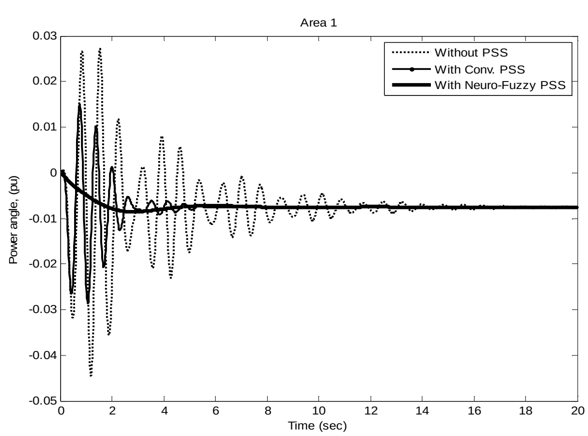

Fig. 9. Dynamic response of Power angle for ΔT_m = 0.004 p.u with Neuro-Fuzzy based PSS controller for Area 1 (P=0.6 p.u, Q=0.7 p.u)

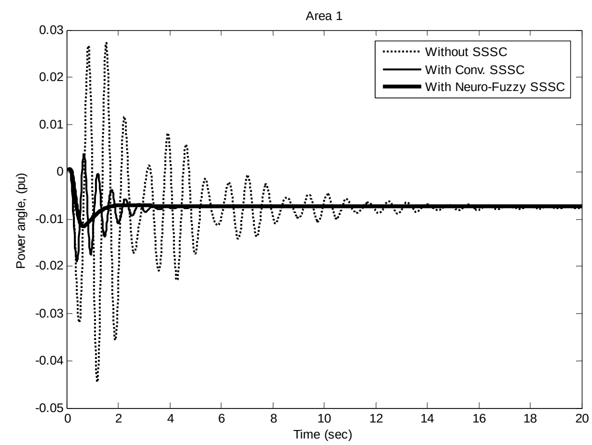

Fig. 10. Dynamic response of Power angle for ΔT_m = 0.004 p.u with Neuro-Fuzzy based SSSC controller for Area 1 (P=0.6 p.u, Q=0.7 p.u)

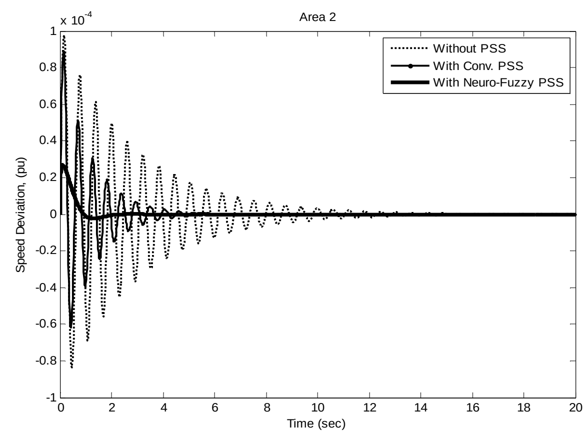

Fig. 11. Dynamic response of Speed deviation for ΔT_m = 0.004 p.u with Neuro-fuzzy based PSS controller for Area 2 (P=0.6 p.u, Q=0.7 p.u)

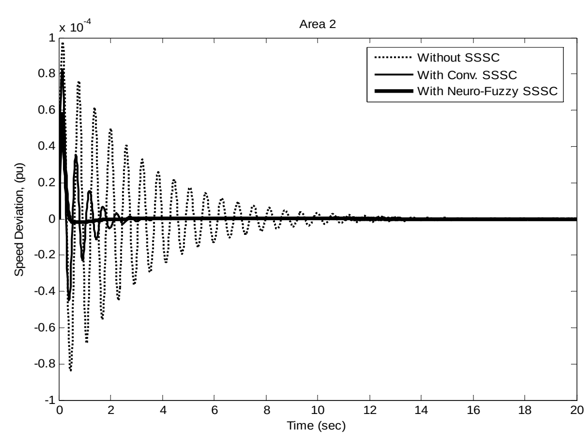

Fig. 12. Dynamic response of Speed deviation for ΔT_m = 0.004 p.u with Neuro-Fuzzy based SSSC controller for Area 2 (P=0.6 p.u, Q=0.7 p.u)

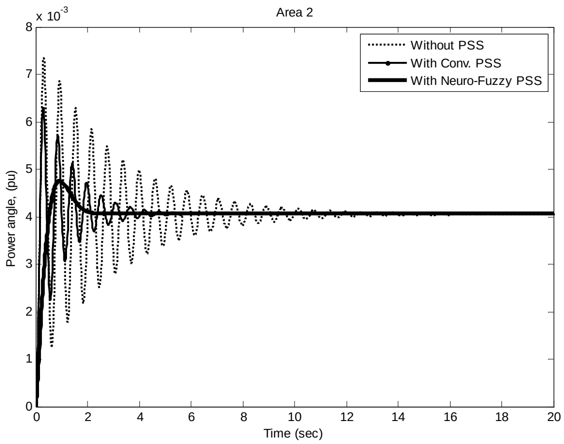

Fig. 13. Dynamic response of Power angle for ΔT_m = 0.004 p.u with Neuro-Fuzzy based PSS controller for Area 2 (P=0.6 p.u, Q=0.7 p.u)

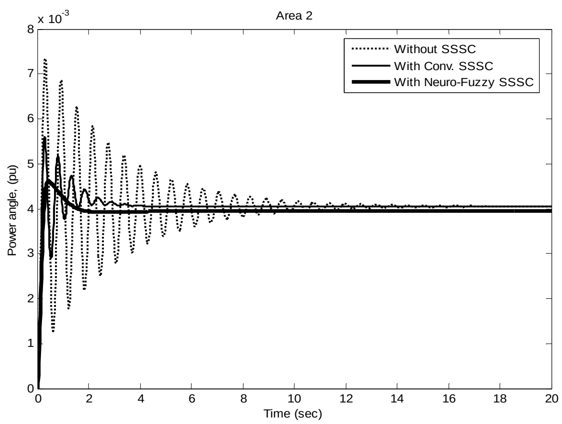

Fig. 14. Dynamic response of Power angle for ΔT_m = 0.004 p.u with Neuro-Fuzzy based SSSC controller for Area 2 (P=0.6 p.u, Q=0.7 p.u)

Without PSS or SSSC controllers, the damping performance of the two-area power system is very poor in terms of increased amplitudes and settling times of oscillations as shown in Figs. 7-14 [18, 19]. 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. 7, 9, 11, and 13, it is inferred that the ANFIS based PSS controllers show good damping performance compared to conventional PSS controllers. Next, the system is simulated with conventional SSSC based damping controllers which show improved damping performance compared to conventional PSS controllers as is seen from the Figs. 8, 10, 12, and 14. Then the ANFIS control approach is employed to conventional SSSC controllers to have still improved damping performance characteristics.

Thus, it is understood from the Figs. 7-14 that the ANFIS based SSSC controllers can provide better damping of speed deviation and 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.

5. Conclusion

In this paper, ANFIS control approach has been applied to PSS and SSSC based damping controllers installed in a two-area power system model. Simulation studies are carried out in Matlab/Simulink environment separately for PSS and SSSC controllers. The fuzzy rules are trained using ANFIS technology. The time domain simulation results validate the efficiency, effectiveness, and robustness of the proposed control scheme, leading to the inference that the ANFIS based SSSC controllers are able to provide better damping of speed deviation and power angle oscillations of the two-area power system in terms of somewhat reduced amplitudes and settling times compared to ANFIS based PSS control scheme under different operating conditions. Even though there are certain changes in the system operating conditions, the easily tunable ANFIS based SSSC controllers are capable of providing fast damping performance.

Appendix

(1). Generators' data:

Generator G1: Rated MVA = 192,
Rated voltage = 18 kV, H(s) = 6.4 MJ / MVA,
$T'_{d0} = 6, \; T'_{q0} = 0.535,$

$x_d = 0.8958, \; x'_d = 0.1198, \; x_q = 0.8645, \; x'_q = 0.1969.$

Generator G2: Rated MVA = 128,
Rated voltage = 13.8 kV, H(s) = 3.01 MJ / MVA,
$T'_{d0} = 5.89, \; T'_{q0} = 0.6,$

$x_d = 1.3125, \; x'_d = 0.1813, \; x_q = 1.2578, \; x'_q = 0.25.$

(2). Transmission line data:

Bus No.	Impedance	
	R	X
1 - 4	0	0.1184
2 - 7	0	0.1823
3 - 9	0	0.2399
4 - 5	0.0100	0.0850
4 - 6	0.0170	0.0920
5 - 7	0.0320	0.1610
6 - 9	0.0390	0.1700
7 - 8	0.0085	0.0720
8 - 9	0.0119	0.1008

(3). Shunt admittances data:

Bus No.	Admittance	
	G	B
4 - 0	0	0.1670
5 - 0	1.2610	-0.2634
6 - 0	0.8777	-0.0346
7 - 0	0	0.2275
8 - 0	0.9690	-0.1601
9 - 0	0	0.2835

Note : All impedance and admittance values are in per unit on 100 MVA base. All time constants are in seconds.

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