Dynamic Stability Improvement of Multimachine Power Systems using ANFIS-based Power System Stabilizer

by Agung Budi Muljono

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Dynamic Stability Improvement of Multimachine Power Systems using ANFIS-based Power System Stabilizer

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Abstract

Modern power system are very vurnerable to against load fluctuation during their operation. Load fluctuation is identified as small disturbance that it is very important in small signal stability (dynamic stability) testing. This research consisted of large scale power system symplification. And, ANFIS-based power system stabilizer (AP) is proposed to improve the dynamic stability of multimachine. The ANFIS method is proposed because the ANFIS computation is more efective than Mamdani fuzzy computation. Simulation results show that the proposed PSS is able to maintain the dynamic stability by decreasing peak overshoot to the value $-3,37 \times 10^{-5}$ pu and accelerating settling time to the time 4.01 s for rotor speed deviation of Machine-2. Also, the peak overshoot is decreased to the value $-1,34 \times 10^{-5}$ pu and the settling time is accelerated to the time 3.98 s for rotor speed deviation of Machine-3.

Keywords: Stability improvement, dynamic, multimachine, PSS, ANFIS

1. Introduction

Modern power systems are cover large area with some generation units connected to bulk power systems via transmission system. Meanwhile, almost of consumers are located in city such as: comercial and official complex areas, suburban area, industrial area and residensial area. Analysis of a large power system is very complicated and difficult. So, simplifiying scheme should be done to solve this difficulties problem. This large system is divide into some small operation areas [1]. The balancing of electrical-mechanical energy is very important to keep the machine works in synchronous mode. Rotor oscillation is a problem during power system operation that appeared of the rotor oscillation due to load fluctuation at load buses. Power system stabilizer (PSS) is applied to damp the rotor oscillation problem. Robust H-infinity loop shapping technique is proposed to damp a single machine in large scale power systems. The proposed PSS ensures to cover a set of pertub operating points with respect to the nominal system and able to maintain the whole system stability [2]. Optimized parameter PSS is used to mitigate the synchronous generator oscillation. Where, a performance index is taken automatically by monitoring the generator parameter. Furthermore, the assessment of the performance index is obtained using an expert system based on waveform record of generator parameter [3].

Identifier and controller scheme based on artificial intelligent algorithm such as: Neural network, fuzzy logic and neuro-fuzzy controllers applied to electrical and other engineering fields are very popular in recent years. A neuro identifier-model reference adaptive controller PSS is applied in single machine and multimachine with online adjusted [4]. An ANFIS model is able to estimate the online critical clearing time (CCT) of transient stability in multimachine power system. Where, the ANFIS model gives the CCT quite satisfied with high accurate solution and low computation time [5]. Support vector machine (SVM) method is applied to transient stability clasification by Maulin *et al*. It is obtained that the SVM method gives better result than multilayer perceptron-neural network (MLP-NN) method [6]. PID-SVC based on recurrent neural network (RNN) has been applied to control chaos and voltage collapse in a power system [7]. Also, ANFIS-based composite controller-SVC and PID-loop have been applied to control chaos and voltage collapse and to regulate the voltage at load bus with loading fluctuation [8][9]. ANFIS controller is used to maintain dynamic response of HVDC system [10]. Furthermore,

ANFIS power system stabilizer (PSS) has been applied to improve the stability of single machine based on feedback linearization [11]. And, adaptive fuzzy rule-based PSS [12] and fuzzy logic PSS [13] [14] are also used to maintain dynamic stability of a power system. Some problem accounts in the large scale power system are method to simplify the large scale power system and control scheme to improve stability of the system.

In order to simplify complex power system, this system was broken down into 3 (three) areas (Area I, Area II and Area III). Then, the multimachine in Area I was regulated by applying ANFIS-based PSS to improve its dynamic stability. This paper is organized as follows: Dynamic stability of a multimacine power system is described in Section 2. Conventional power system stabilizer design and ANFIS algorithm are detailed in Section 3 and 4, respectively. Next, simulation result and analysis are presented in Section 5. And, the conclusion is provided in the last section.

2. Dynamic Stability of a Multimachine Power System

A multimachine power system in this research is given by Padiyar [15]. This system consist of 39-bus, 10-machine, and this system is shown in Figure 1. The system was separated into Area I with Machine-1, Machine-2 and Machine-3. Area II: Machine-4, Machine-5, Machine-6 and Machine-7. And, Area III: Machine-8, Machine-9 and Machine-10.

Stability of the multimachine in Area I is focused on this research included electro-mechanical interaction in 3-machine model. Therefore, the Machine-1 at Bus 1 was threated as a reference/swing bus. Furthermore, the speed and angle rotor deviation of the Machine-1 was taken as zero, respectively. Mechanical and reactive mode equipped by exciter tipe IEEE 1a were used to represent the classical model of each machine.
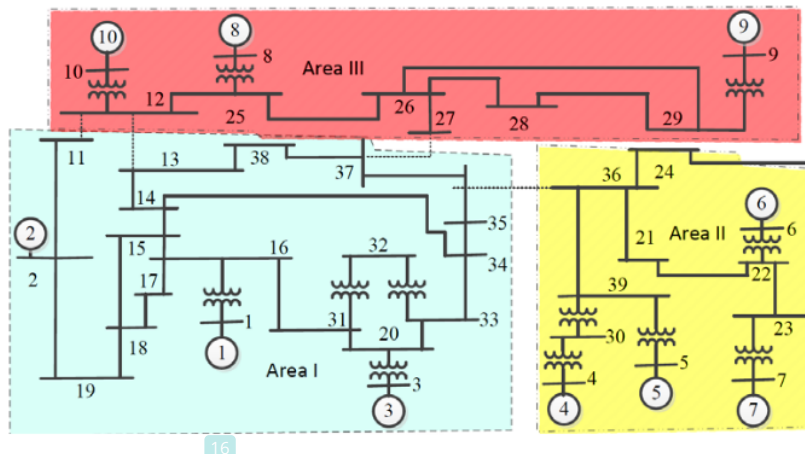

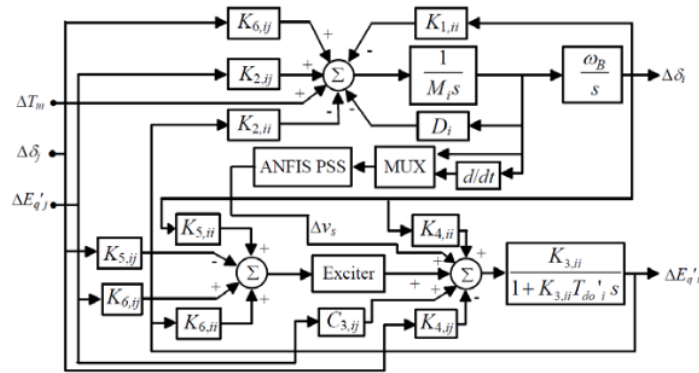Figure 1. Single line diagram of a multimachine power system

Figure 2. Linear model of ith machine equipped by ANFIS-PSS in a multimachine power system

Stability is the ability of power system to cover the disturbance at normal operation the effort to maintain the power system going to steady state after the disturbance is diappeared. Small signal (dynamic) stability included one or some machines were changed the operating point moderately. Dynamical behavior of the system is depended on interaction of turbine, generator, also the controller characteristic such as governor and excitation systems. Formulas for represented the dynamical system of the ith machine in linear model are as follows [16]:

$$\Delta\dot{\delta_i} = \omega_0\Delta\omega_i, \tag{1}$$

$$\Delta\dot{\omega_i} = \frac{1}{M_i}(\Delta T_{mi} - \Delta T_{ei} - D_i\Delta\omega_i), \tag{2}$$

where ΔT_{mi}, ΔT_{ei}, M_i, D_i, $\Delta\omega_i$ and $\Delta\delta_i$ are the mechanical torque, electrical torque, inertia constant, damping constant, rotor speed and rotor angle deviation of macine ith, respectively. And ω_0 is the synchronous speed. Synchronous machine components to represent the dynamic stability analysis are divide into mechanical and reactive component (mode). The mechanical and reactive mode to illustrate a multimachine power system equipped by PSS in linear model is illustrated by diagram block in Figure 2. This linear system can be described by state space or Laplace form for time or frequency domain, respectively. The model formulas are as follows:

$$\text{State space: } \begin{matrix} \Delta\dot{x}(t) = \Delta Ax(t) + \Delta Bu(t), \\ \Delta y(t) = \Delta Cx(t) + \Delta Du(t), \end{matrix} \quad \text{Laplace: } \begin{matrix} s\Delta x(s) - \Delta x(0) = A\Delta x(s) + B\Delta u(s) \\ \Delta y(s) = \Delta Cx(s) + \Delta Du(s) \end{matrix} \tag{3}$$

3. Conventional PSS

The function of the PSS is to provide damping torque component to the generator (machine) rotor oscillation by regulating its excitation system through an additional stabilizing signal. To provide the damping torque, the stabilizer must produce a component of electrical torque in phase with the rotor speed deviation. The PSS device is very important to improve stability of overall power systems. Since the porpuse a PSS is to introduce a damping torque component, a logical signal to use for regulating excitation system of machine is rotor speed deviation. And, PSS output is an additional stabilizing signal (ΔV_s). Conventional PSS device consist of gain, washout and phase compensation blocks. The gain block determines the amount of damping introduce by the PSS. The signal washout block serves as a high frequency filter, with the time constant T_w. The phase compensation bock provides the appropriate phase lead characteristic to compensate the phase lag between exciter input and generator (air-gap) electrical torque. Diagram block of conventional PSS is shown in Figure 3(a).

4. Adaptive Neuro Fuzzy Inference System

Adaptive neuro-fuzzy inference system is one of method based on artificial intelligent. The ANFIS method function is same as the fuzzy rule based on Sugeno algorithm. The ANFIS is consist of premis and consequence parameters. So, both the parameters were obtained by off-line learning processes with least squares estimation (LSE) and backpropagation algorithms. At forward step, the parameters were identified by using LSE method. Moreover, at backward step, the error signal was attenuated back, and the parameters were maintained by using gradient descent optimization. Suppose that the ANFIS network has 2 (two) inputs x, y and an output O. This ANFIS model has 2 rules and based on first-order fuzzy Sugeno. The rules are as follows [17]:
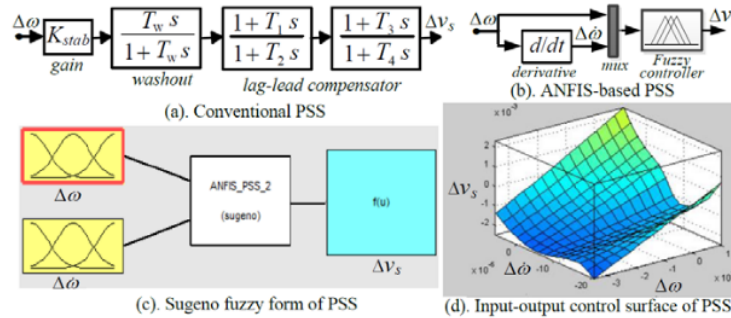
Figure 3. PSS block diagram

1: If x is A_1 and y is B_1 Then $y_1 = p_1 x + q_1 y + r_1$
2: If x is A_2 and y is B_2 Then $y_2 = p_2 x + q_2 y + r_2$,
Finally, output the ANFIS network is follow:

$$O_i = \sum_i \overline{w}_i f_i = \frac{\sum_i w_i f_i}{\sum_i w_i},$$

After the ANFIS algorithm has been built. Therefore, the ANFIS-based PSS in this scheme control was applied to replace the function of the conventional PSS. The ANFIS-based PSS block diagram is illustrated in Figure 3(b).

5. Building Process of ANFIS-based Power System Stabilizer

Before the ANFIS-based PSS is applied to a multimachine system, the proposed PSS is designed and constructed by some learning processes in off-line mode. Data training that used for this learning process were obtained by simulating the multimachine equipped with conventional PSS. To obtain the data training, a multimachine system with conventional PSS is forced by single and multiple step functions. Where the step function was used to implement the change of mechanical torque in the machine due to load fluctuation. In this learning process, a 4000-data training set was used to design the ANFIS-based PSS. The inputs of ANFIS-based PSS were rotor speed deviation ($\Delta\omega$) and its derivative ($\Delta\dot{\omega}$). And, the output was an additional stabilizing signal (ΔV_s). Structure of the ANFIS PSS model was built by using 7 (seven) Gaussian membership functions for the input and 49 (forty-nine) rules fuzzy Sugeno orde 1 for the output, respectively. After some learning processes were conducted, the Sugeno fuzzy form of the PSS was built automatically. This Sugeno fuzzy form of the PSS is illustrated in Figure 3(c). And, control surface of respective input-output the ANFIS-based PSS was obtained. A set of input-output control surface was obtained as follow: $\Delta\omega$-$\Delta\dot{\omega}$-ΔV_s. This input-output control surface of PSS is shown in Figure 3(d).

6. Results and Analysis

To demonstrate the performance of a multimachine power system, this multimachine system was examined using Matlab/Simulink 7.9.0.529 (R2009b) [18] on an Intel Core 2 Duo E6550 233 GHz PC computer and windows 7 64-bit (win64) operating system. The simulations were done as follows:
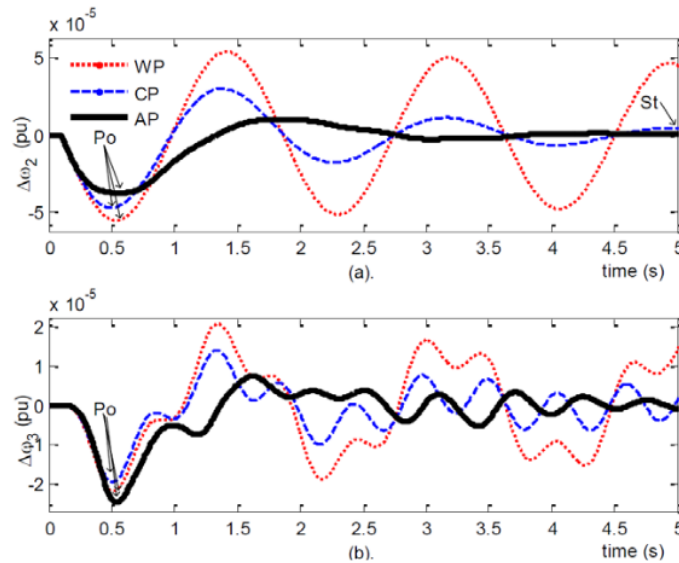

Figure 4. Improvement of the rotor speed deviation on a single distrubance

6.1. Performance of Proposed PSS at a Single Disturbance

A multimachine power system Area I is run without any control scheme. Next, the system is equipped by 2 (two) conventional PSS(s) at Machine-2 and Machine-3. And, 2 (two) ANFIS-based (proposed) PSS(s) were applied at respective machine to maintain the system responses. First Scenario, the system was forced by a single disturbance at machine-2 (mechanical torque deviation, ΔT_1) at the value of 0.1 pu and the time of 0.1 s. The responses of the system were observed at their rotor speed and angle deviation. These simulation results are illustrated in Figures 4, 5, and listed in Table 1.

Figure 4(a) and Table 1 show the proposed PSS (AP) was able to improve the peak overshoot (Po) of the rotor speed deviation ($\Delta\omega_2$) at the value of -3.37×10^{-5} pu. The settling time (St) was also improved at the time of 4.01 s. Meanwhile, the conventional PSS (CP) and the multimachine without any PSS (WP) gave the peak overshoot at the values of -4.65 and -5.50×10^{-5} pu, respectively. So, the settling time of the CP and WP were achived at times of 6.45 and >20 s. Figure 4(b) and Table 1 ilustrate the peak overshoot improvement of rotor speed deviation ($\Delta\omega_3$) by the proposed PSS at the value of -1.34×10^{-5} pu. Also, the settling time of the $\Delta\omega_3$ was achieved at the value of 3.98 s for the proposed PSS. While, when the system was equipped by the CP and WP, the system achieved the peak overshoot at the values of -1.83 and -2.21×10^{-5} pu, respectively. And, the other PSS(s) achieved the settling time at times of 6.39 and >20 s.

The peak overshoot of rotor angle deviation ($\Delta\delta_2$) was also maintained by the proposed PSS at the value of $-0.46°$. The CP and WP gave the peak overshoot at the values of -0.56 and $-0.67°$, respectively. Moreover, the steady state of the rotor angle deviation was achieved at $-0.34°$. The settling time of the proposed PSS was at time of 4.32 s. Meanwhile, the settling time of the other PSS(s) were at times of 5.37 and >20 s, respectively. These responses are

illustrated in Figure 5(a) and Table 1. Figure 5(b) and Table 1 show the responses of rotor angle deviation for Machine-3 ($\Delta\delta_3$). It is described that the peak overshoot was achieved at the value of $-0.135°$. The peak overshoot for the CP and WP were at the values of -0.163 and $-0.195°$. The rotor angle steady state (Ss) was achived at the value of $-0.094°$ for all PSS(s). The settling time of the proposed PSS was achived at time of 4.09 s. Meanwhile, the settling time of the CP and WP were obtained at time of 6.32 and >20 s.
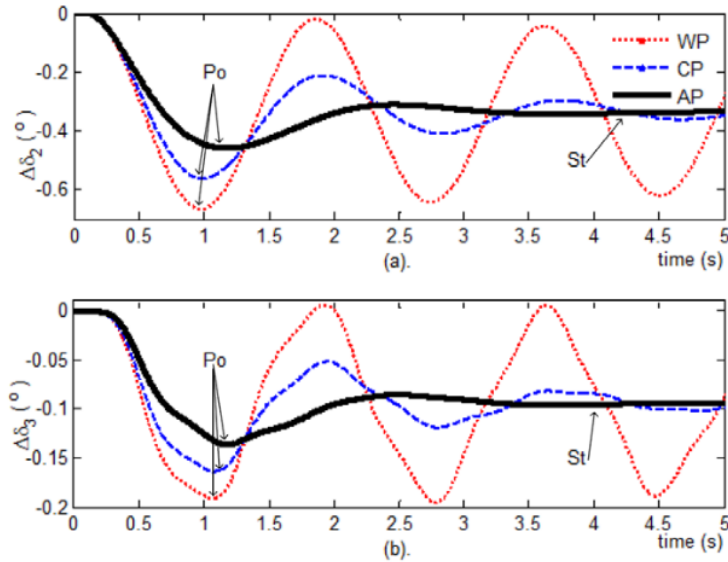
Figure 5. Improvement of the rotor angle deviation on a single disturbance

Table 1. Responses of a system without (WP), with conventional (CP) and ANFIS (AP) PSS(s).

PSS	$\Delta\omega_2$			$\Delta\delta_2$		
	Peak overshoot (Po) $\times10^{-5}$ (pu)	Settling time (St) (s)	Po (°)	St (s)	Ss (°)
WP	−5.50	> 20	−0.67	> 20	
CP	−4.65	6.45	−0.56	5.37	−0.34
AP	−3.37	4.01	−0.46	4.32	
PSS	$\Delta\omega_3$			$\Delta\delta_3$		
	Po $\times10^{-5}$ (pu)	St (s)	Po (°)	St (s)	Ss (°)
WP	−2.21	> 20	−0.195	> 20	
CP	−1.83	6.39	−0.163	6.32	−0.094
AP	−1.34	3.98	−0.135	4.09	

In First Scenario, it is shown that the proposed PSS is able to give better performance than the other PSS. Where, the proposed PSS produces peak overshoot values of rotor speed and angle are less than that the peak overshoot of the other PSS. Also, settling time of the proposed PSS of all responses are shorter than that the settling time of the others.

6.2. Performance of Proposed PSS at Multiple Disturbances
Second Scenario, 2 (two) disturbances were forced to the multimachine system, where the mechanical torque deviation (ΔT_1) was applied on Machine-2 and ΔT_2 was applied on Machine-3 at the value of 0.0065 pu and time of 5.0 s. Graphical visualization and numerical values of the responses are discribed in Figures 6, 7 and Table 2, respectively.

Maintenance of the Machine-3 rotor speed deviation ($\Delta\omega_3$) was achieved when the system equipped by the proposed PSS. The peak overshoot and settling time of this response were at the value of -1.06×10^{-5} pu and time of 5.91 s, respectively. The peak overshoot responses of conventional PSS (CP) and without any PSS (WP) were obtained at the values of -1.48×10^{-5} and -2.13×10^{-5} pu. And, the settling time responses of the CP and WP were achieved at times of 7.46 and >20 s. These responses are illustrating and listing in Figure 6(b) and Table 2. On the other hand, simulation shows that the effect of the mechanical torque (ΔT_2) disturbance to the rotor speed deviation of Machine-2 ($\Delta\omega_2$) response was very small. So, this effect can be neglected. This response is shown in Figure 6(a).
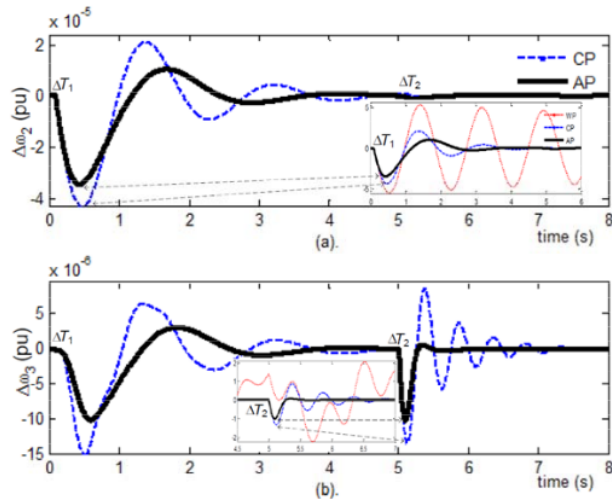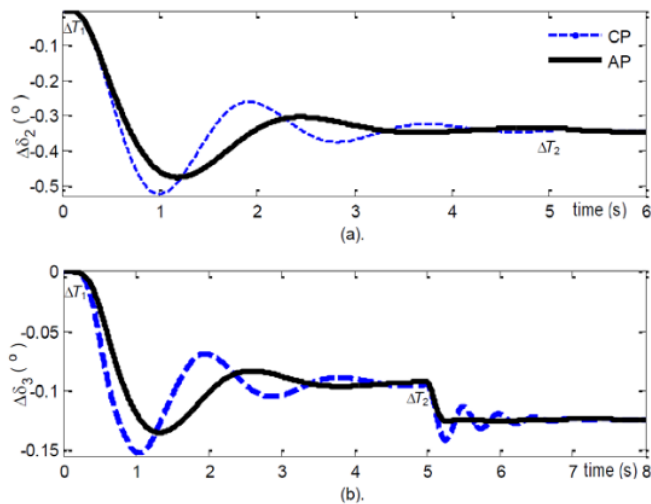

Figure 6. Dynamic stability improvement of rotor speed on the multiple disturbances

Figure 7. Dynamic stability improvement of the rotor angle deviation on multiple disturbances

Figure 7(a) and Table 2 show the peak overshoot and settling time of the rotor angle deviation Machine-2 ($\Delta\delta_2$) was achieved at the value of −0.341° and time of 5.21 s for the proposed PSS, respectively. While, the peak overshoot of the system for conventional PSS (CP) and without any PSS (WP) was at the values −0.342 and −0.67°. And, steady state value of the $\Delta\delta_2$ was at −0.3405°. The settling time for the CP and WP was at the times of 6.07 and >20 s.

Finally, improvement response of the proposed PSS was achieved at the value of −0.123° and time of 5.23 s for the rotor angle deviation of Machine-3. On the other hand, the peak overshoot of the CP and WP was achieved at the values of −0.147° and −0.214°. And, the steady state value for all PSS was achieved at −0.122°. Moreover, the settling time for the CP and WP was at times of 6.84 and >20 s, respectively. These simulation results are illustrated in Figure 7(b) and Table 2.

Simulation results show that the proposed PSS is able to maintain dynamic stability of a multimachine significantly in this research. Where, the performance of the proposed PSS is tested with a single disturbance in First Scenario and multiple disturbances in Second Scenario. The proposed PSS gives a better performance than the other PSS for a single and multiple disturbances. The stability improvement is achieved by reducing the peak overshoot and accelerating the settling time of rotor speed. Also, the peak overshoot and accelerating the settling time of the angle deviation are improved for respective machine. And, the performance of the proposed PSS are compared to the responses of conventional PSS and without any PSS to check validity of the results.

Table 2. Improvement of a system when the mechanical torque is forced to Machine-3 (ΔT_2) at time 5.0 s

PSS	$\Delta\omega_2$ Peak overshoot (Po) $\times10^{-5}$ (pu)	Settling time (St) (s)	Po (°)	$\Delta\delta_2$ St (s)	Ss (°)
WP	−5.3	> 20	−0.67	> 20	
CP	−0.13	5.94	−0.342	6.07	−0.3405
AP	−0.10	5.23	−0.341	5.21	
PSS	$\Delta\omega_3$ Po $\times10^{-5}$ (pu)	St (s)	Po (°)	$\Delta\delta_3$ St (s)	Ss (°)
WP	−2.13	> 20	−0.214	> 20	
CP	−1.48	7.46	−0.147	6.84	−0.122
AP	−1.06	5.91	−0.123	5.23	

7. Conclusion

This research is stressed on improvement of dynamic stability a multimachine system using ANFIS-based power system stabilizer (proposed PSS). The proposed PSS function is to provide additional stabilizer signal as a torque damping component to reduce rotor oscillation. The rotor oscillation is appeared when the system is forced by a dynamical disturbance such as load changed or load fluctuation. The ANFIS model is used in this research because the ANFIS model is more effective than the Mamdani fuzzy model. The ANFIS-based PSS is training by the data that obtained by simulating conventional PSS. All the training processes are conducted in off-line mode. Rotor speed deviation and its derivative are used as inputs of the ANFIS-PSS and the additional signal stabilizer of the PSS is taken as an output. Structure of ANFIS input is built by Gaussian membership function and it output is built by Sugeno fuzzy orde 1. Next, the proposed PSS is applied to a multimachine system and the system is forced by a single disturbance. The simulation results show that responses of the proposed PSS are better than that responses of the other PSS. Where, the peak overshoot of the rotor speed deviation of the proposed PSS is obtained at the values of −3.37×10⁻⁵ and −1.34×10⁻⁵ pu for Machine-2 and Machine-3. The peak overshoot of the rotor angle deviation is obtained at the values of −0.46 and −0.135° for Machine-2 and Machine-3, respectively. The settling time of the rotor speed deviation is achieved at times of 4.01 and 3.98 s, for Machine-2 and Machine-3. And, the settling time of rotor angle deviation is achieved at times of 4.32 and 4.09 s for Machine-2 and Machine-3, respectively. Furthermore, the proposed PSS is also able to against multiple disturbances. Where, the proposed PSS gives better responses than that responses of the

other PSS when the system is forced by the multiple disturbances. Some efforts should be done to improve stability of the whole multimachine system. In the future research, the proposed PSS should be applied to the other machine in Area II and III to test their responses on all system.

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