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Coordination of Adaptive Neuro Fuzzy Inference System (ANFIS) and Type-2 Fuzzy Logic System-Power System Stabilizer (T2FLS-PSS) to Improve a Large-scale Power System Stability

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Article Info

ABSTRACT

Intelligent control included ANFIS and type-2 fuzzy (T2FLS) controllers grown-up rapidly and these controllers are applied successfully in power system control. Meanwhile, small signal stability problem appear in a large-scale power system (LSPS) due to load fluctuation. If this problem persists, and can not be solved, it will develop blackout on the LSPS. How to improve the LSPS stability due to load fluctuation is done in this research by coordinating of PSS based on ANFIS and T2FLS. The ANFIS parameters are obtained automatically by training process. Meanwhile, the T2FLS parameters are determined based on the knowledge that obtained from the ANFIS parameters. Input membership function (MF) of the ANFIS is 5 Gaussian MFs. On the other hand, input MF of the T2FLS is 3 Gaussian MFs. Results show that the T2FLS-PSS is able to maintain the stability by decreasing peak overshoot for rotor speed and angle. The T2FLS-PSS makes the settling time is shorter for rotor speed and angle on local mode oscillation as well as on inter-area oscillation than conventional/ ANFIS-PSS. Also, the T2FLS-PSS gives better performance than the other PSS when tested on single disturbance and multiple disturbances.

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1. INTRODUCTION

Controller based on artificial intelligent is the research topic interest in recent year. Because the intelligent control has learning ability to improve its performance from the environment where the controller is applied. The spreading of intelligent control exists on some fields such as: Electrical and electronic engineering, and computer science such as: Fuzzy controller is used to enhance photovoltaic generator power quality by maintaining the MPPT tracking on low voltage side of DC/DC boost converter. The MPPT-fuzzy controller is able to maintain voltage profile and current total harmonic distortion (THD) [1]. The performance of fuzzy controller is compared to the PI controller on two inverter fed to control six-phase permanent magnet synchronous machine (PMSM) operated as a motor. The simulation results show that the fuzzy controller are more robust, quick response on high starting torque and more effective the PI controller [2]. Support vector machine (SVM) method is used to classify a large-scale power system transient stability. The SVM method gives a better result than multi-layer perceptron-neural network (MLP-NN)

method [3]. Adaptive neuro-fuzzy inference system (ANFIS) controllers have been implemented in 3-machine 9-bus power systems. Where, the ANFIS controllers are able to maintain the dynamic stability of the multimachine power systems significantly [4], [5]. Neural network controller is used as a feedback control to improve the dynamic performance of single synchronous machine connected to infinite bus [6]. Adaptive fuzzy rule-based PSS [7] and fuzzy logic PSS [8], [9] are also successful applied to maintain dynamic stability of a power system. Meanwhile, Type-2 fuzzy logic system (T2FLS) is applied to coordination of excitation and governor systems [10]. In [11], the T2FLS is used as a PSS and tuning of its parameter is optimized by differential evolution algorithm to cover the uncertainty of disturbances. An indirect adaptive T2FLS-PSS is implemented to damp out of the low frequency oscillation on different operating condition of a power system [12].

While, power system companies that serve consumers on a wide-area continuously with standard quality assurance and without interruption. Some generation units such as: Hydro, thermal, nuclear and gas power plants are connected to bulk power systems via interconnecting transmission line including high voltage direct current (HVDC) system. On the other hand, almost of consumers are located in city areas such as: Trade/commercial and official complex areas, suburban area, industrial area and residential area. Analysis of a large-scale power system (LSPS) network is usually very complicated and difficult. The simplifying scheme should be done to resolve this complicated network problem. In this research, the LSPS is divide into three parts of small operation areas [13]. In operation time, imbalance of energy in respective synchronous machine makes the rotor machine oscillate due to load fluctuation at one or some load buses. When the rotor machines are oscillate continuously without any control scheme, this situation can cause the LSPS going into instability problem.

To cover this rotor oscillation problem, power system stabilizer (PSS) is proposed at excitation system of synchronous machine to damp the rotor oscillation. Where, local mode stability of a pump storage power plant is significantly improved by using the PSS [14]. Furthermore, performance of a conventional PSS is maintained by using additional or auxiliary loop [15]. PSS based on optimal and sub-optimal linear quadratic regulator design are proposed to improve stability of power system. In this design, only speed deviation and PSS states are considered as the inputs, while the coupling gain between machines are neglected [16]. The function of conventional control is instead by the neural network, fuzzy or neuro-fuzzy controls. Proportional integral and derivative-static var compensator based on recurrent neural network is applied to control chaos and voltage collapse in a power system. This control scheme is able to suppress chaos and voltage collapse in power systems [17]. Adaptive critic design based (ADC) neuro-fuzzy controller is applied to control the static compensator in a LSPS. It is shown that the ADC neuro-fuzzy controller is more effective than PI controller in responding to small disturbance and short circuit fault [18]. Also, a Mamdani fuzzy controller is applied to hardware implementation to static compensator in a LSPS [19]. The ANFIS-based composite controller-SVC and PID-loop are applied to control chaos and voltage collapse and to regulate the voltage at load bus with loading fluctuation [20], [21]. Also, the ANFIS controller is tried to maintain dynamic response of HVDC system [22] and to protect the HVDC devices from the short circuit [23]. Furthermore, ANFIS power system stabilizer (PSS) has been applied to improve the stability of single machine based on feedback linearization [24].

According to wide range usability and previous research of the ANFIS and T2FLS applications in power system. We aim to evaluate the control strategy of ANFIS and T2FLS-based power system stabilizer to improve stability of a large-scale power system in this research. Where, the ANFIS method is used in this research because the ANFIS is able to train from time-series data. Parameters of ANFIS controller are obtained by training processes in off-line mode. The parameters of ANFIS controller are adjusted automatically during the training processes using data training. The data training is obtained by simulating the system equipped with conventional PSS and load capacity of the LSPS is varied. Meanwhile, T2FLS method is used in this research because the T2FLS is able to cover the input, membership function, and output with uncertainty. Also, T2FLS membership function and rules are designed based on the knowledge of the designer. The paper is organized as follows: Stability of a power system is described in Section 2. Design of ANFIS and T2FLS-based power system stabilizer is explained in Section 3. Next, result and discussion are presented in Section 4. And, the conclusion is provided in the last section.

2. POWER SYSTEM STABILITY

Stability is defined as 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 disappeared. Dynamical behavior of a single machine connected to infinite bus is depended on interaction of turbine, generator, also the controller characteristic such as governor and excitation systems. Dynamical of a single machine formulas in linear model are as follows [25] :

$$\Delta\dot{\delta} = \omega_0\Delta\omega \tag{1}$$

$$\Delta\dot{\omega} = \frac{1}{M}(\Delta T_m - \Delta T_e - D\Delta\omega) \tag{2}$$

A large-scale power system (LSPS) consists of two or more local power system areas. Topology of existing LSPS usually follows the geographic surfaces. Which is the local area is connected to the other by transmission line to form the LSPS. The LSPS in this research is taken from Padiyar [26]. This system consist of 39 buses and 10 machines. Furthermore, the system was simplified to Area I, Area II and Area III, and shown in Figure 1. The Machine-1 (M_1) at Bus 1 was treated as a reference bus. Furthermore, the speed and angle rotor deviation was taken as zero values, respectively.
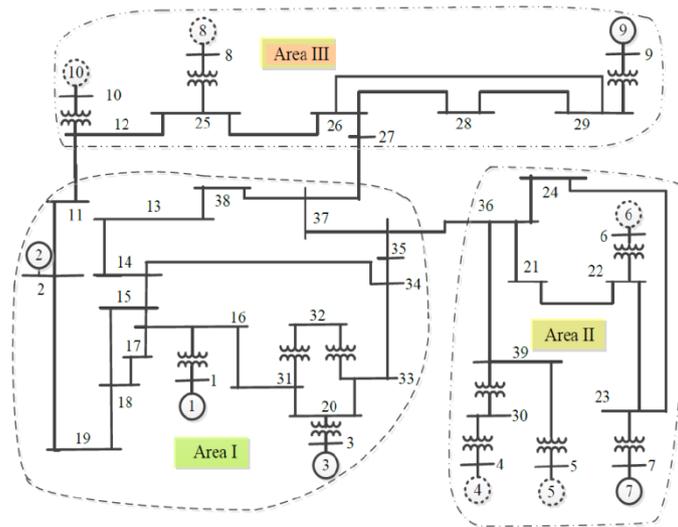

Figure 1. A large-scale power system

Power system stabilizer (PSS) provides additional damping to rotor oscillation of machine by regulating its excitation system through an additional stabilizing signal. The PSS produces an electrical torque component in phase with the rotor speed deviation to provide the additional damping torque. The PSS is very important to improve stability of overall power systems. Since the PSS is to introduce a damping torque component, a logical signal to use for regulating excitation system of machine is rotor speed deviation. And, output of the PSS is the additional voltage compensation that feeding to the excitation system. Conventional PSS 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_ω. The phase compensation block provides appropriate phase lead characteristic to compensate the phase lag between exciter input and generator (air-gap) electrical torque.

3. DESAIN OF PSS BASED ON ARTIFICIAL INTELLIGENT
3.1. PSS based on ANFIS Controller
An adaptive neuro-fuzzy inference system or adaptive network-based fuzzy inference system (ANFIS) is a kind of artificial neural network that is based on Takagi–Sugeno fuzzy inference system. Since it integrates both neural networks and fuzzy logic principles, it has potential to capture the benefits of both models in a single framework. Its inference system corresponds to a set of fuzzy IF-THEN rules that have learning capability to approximate nonlinear functions.

Hence, ANFIS is considered to be a universal estimator. The ANFIS consists of premise and consequence parameters. The ANFIS function is same as the fuzzy rule based on Sugeno algorithm. So, both the parameters are obtained by off-line learning processes with least squares estimation (LSE) and back-propagation algorithms. At forward step, the parameters are identified by using LSE method. And, at backward step the parameters are maintained by using gradient descent optimization. Suppose that the

ANFIS network has 2 (two) inputs *x, y* and an output *O*, with 2 (two) rules based on first-order fuzzy model Sugeno [27]:

$$R_1^A: \text{If } x \text{ is } A_1 \text{ And } y \text{ is } B_1 \text{ Then } y_1 = p_1 x + q_1 x + r_1$$
$$R_2^A: \text{If } x \text{ is } A_2 \text{ And } y \text{ is } B_2 \text{ Then } y_2 = p_2 x + q_2 x + r_2$$

(3)

Output of the ANFIS-network is formulated follow:

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

(4)

The ANFIS-based PSS is designed by some learning processes in off-line mode. Data training that used for this learning process were obtained by simulating the conventional PSS. To obtain the data training, the LSPS is equipped by conventional PSS. The result of the training stage was the ANFIS-based PSS and this PSS was applied to replace the conventional PSS. And, the ANFIS-based PSS membership function for rotor speed deviation is illustrated in Figure 2.
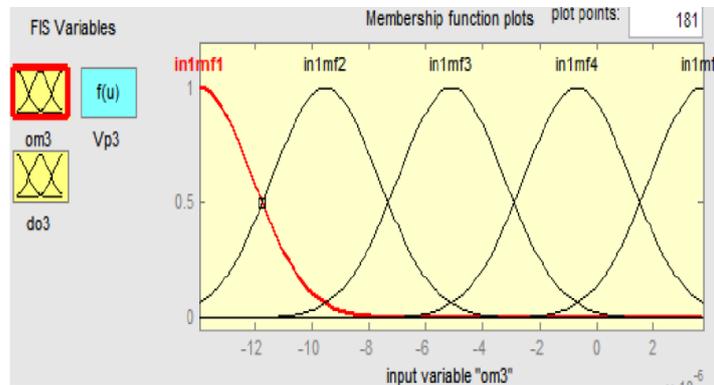

Figure 2. Membership function for input ANFIS of $\Delta \omega_3$

3.2. PSS based on Type-2 Fuzzy Logic System (T2FLS) Controller

Type-2 fuzzy system is a class of fuzzy logic system which the antecedent or consequent membership functions are type-2 fuzzy sets. The concept of a type-2 fuzzy set is defined as an extension of the concept of an ordinary set (henceforth call a type-1 fuzzy set). The structure of a T2FLS is quite similar to a T1FLS. The difference is that on the antecedent and/or consequent sets of the T2FLS are type-2 and each rule output set is a type-2 also. The T2FLS consist of five parts such as [28], [29]: Fuzzifier, rule base, inference engine, type reducer and defuzzifier parts. Block diagram of type-2 FLS and membership function of input $\Delta \omega_3$ are shown in Figure 3(a) and Figure 3(b), respectively.
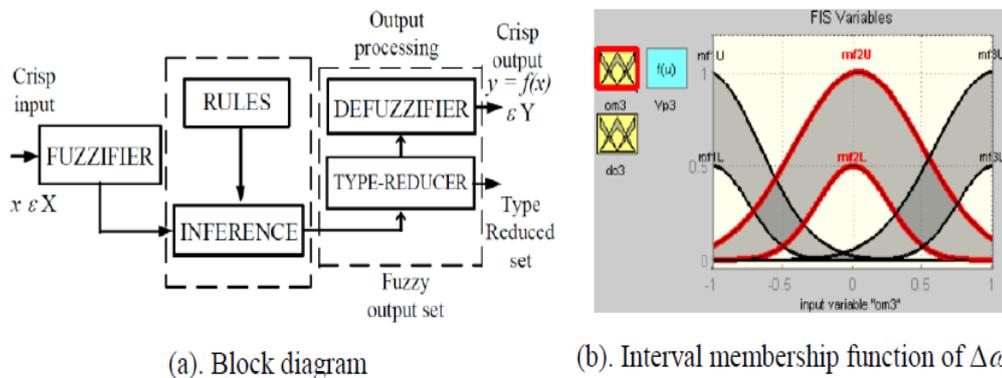

(a). Block diagram   (b). Interval membership function of $\Delta \omega_3$

Figure 3. PSS based on the type-2 logic fuzzy system

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a. Fuzzifier

   The fuzzifier maps a crisp input vector with n input fuzzy sets. Singleton type-2 fuzzy input sets ($\tilde{A}_x$) are considered in this research. Where, in the singleton fuzzification, the input fuzzy set has only a single point of non-zero membership. So, the $\tilde{A}_x$ is a T2 fuzzy singleton if $\overline{\mu}_x = 1$ for $x_i = x_i^0$ and $\mu_{\tilde{A}_x}(x_i) = 0$ for all $x_i \neq x_i^0$, $(i = 1,2,\cdots,n)$.

b. Rule base

   For an interval type-2 fuzzy logic system (IT2FLS), the j-th is written as follows:

$$R^j: \text{If } x_i \text{ is } V_1^j \text{ and,..., If } x_n \text{ is } V_n^j \text{ Then } y_p \text{ is } \Theta^j \tag{5}$$

where the V_1^j are antecedent type-2 sets, $y \in Y$ is the output and Θ^j are the consequent T2 sets. This rule represents a T2 fuzzy relation between the input and the output space on the FLS.

c. Fuzzy Inference

   For the IT2FLS, product operation is considered to implement with minimum or t-norm, the firing interval V^j of the j-th rule is an interval type-2 set, which is determined by its left most point and right most point $\underline{v}^j$ and $\overline{v}^j$:

$$V^j(X^0) = \left[\underline{v}^j(X^0), v^j(X^0)\right] = \left[\underline{v}^j, \overline{v}^j\right] \tag{6}$$

where X^0 is the instantaneous value of X. The firing interval bounds for the j-th rule of an IT2FLS with n inputs $\underline{v}^j$ and $\overline{v}^j$ are written as follows:

$$\underline{v}^j = \underline{\mu}_{v1}^j(x_1^0) * \cdots * \underline{\mu}_{vn}^j(x_n^0) = \prod_{i=1}^n \underline{\mu}_{vi}^j(x_i^0) \tag{7}$$

$$\overline{v}^j = \overline{v}_{v1}^j(x_1^0) * \cdots * \overline{v}_{vn}^j(x_n^0) = \prod_{i=1}^n \overline{v}_{vi}^j(x_i^0) \tag{8}$$

d. Type Reduction

   Type reduction process aims to change the T-2 output of inference system to a type-1 set. Where, center of sets (COS) type reduction method is considered in this research. This method is more effective computation than other methods and requires less time computation. The COS method is written as follows:

$$Y_{COS} = \frac{\sum v^j}{\sum v^j \theta^j} d\theta^1 \cdots d\theta^r dv^1 \cdots dv^r \tag{9}$$

where Y_{COS} is the interval set determined by two end points $y_l(X)$ and $y_r(X)$, $\theta^j \in \Theta^j = \left[\theta_l^j, \theta_r^j\right]$ is the type-2 interval consequent set and, $v^j \in V^j = \left[\underline{v}^j, \overline{v}^j\right]$ is the firing interval.

e. Defuzzification

   Next, the type reduced set Y_{COS} is determined by its left most point $y_l(X)$ and right most point $y_r(X)$. Using the center of gravity, the defuzzified crisp output is given by

$$y = \frac{y_l + y_r}{2} \tag{10}$$

In this research we use Matlab/Simulink toolbox to generate the type-2 fuzzy logic system that provided by Taskin and Kumbasar [30], [31].

4.   RESULT AND DISCUSSION

   Three PSS types are applied to improve the stability of a large-scale power system in this research. The simulation procedure are as follows: The Machine-2 (M_2) is equipped by ANFIS-PSS. While, the Machine-3 (M_3), Machine-7 (M_7) and Machine-9 (M_9) are equipped by conventional, ANFIS and T2FLS-PSS. The responses are observed on $\Delta\omega_3$ and $\Delta\delta_3$ for local mode oscillation. Also, the responses are observed

on $\Delta\omega_7$, $\Delta\omega_9$, $\Delta\delta_7$ and $\Delta\delta_9$ for inter-area mode oscillation. The proposed PSS is implemented using the Matlab/Simulink [32] on an Intel Core 2 Duo E6550 @ 2.33 GHz PC computer.

4.1. Performance of Respective PSS on a Single Disturbance

First Scenario, PSS(s) based on ANFIS and Fuzzy type-2 are evaluated by forcing a single step mechanical disturbance on Machine-2 at 0.1 pu. When the system was disturbed and simulation results were observed on the Figure 4, Figure 5 and Figure 6. Also, the result is listed in Table 1.
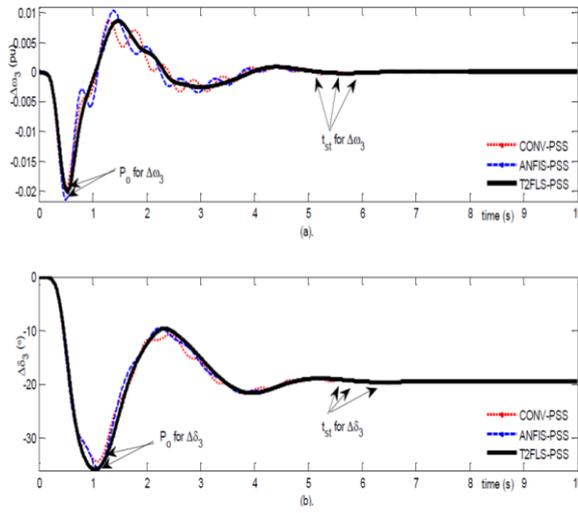

Figure 4. Stability improvement on (a) $\Delta\omega_3$ and (b) $\Delta\delta_3$ when forced by a single disturbance
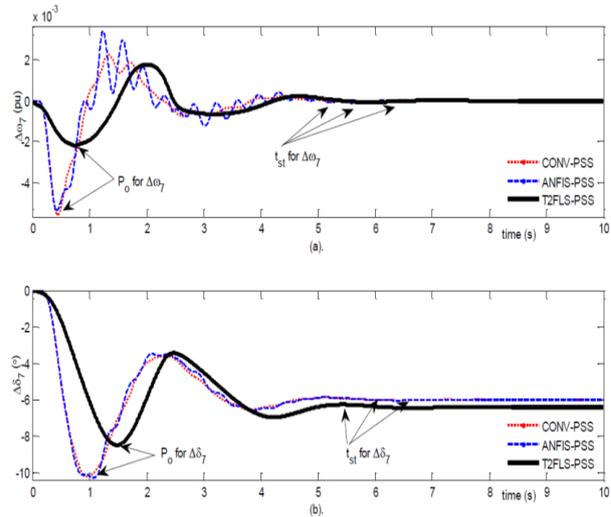
Figure 5. Enhancement of the (a) $\Delta\omega_7$ and (b) $\Delta\delta_7$ responses using T2FLS-PSS

Figure 4(a) and Table 1 show the peak overshoot (P_o) of the rotor speed deviation ($\Delta\omega_3$) was obtained at the values of −20.14, −21.42 and −19.85×10^{-3} pu for the T2FLS-PSS, ANFIS-PSS and CONV-PSS, respectively. In this result, the settling time was achieved at the times of 5.25, 5.72 and 5.97 s, respectively. Figure 4(b) and Table 1 are responses for rotor angle deviation of M_3. It is shown that the peak overshoot was achieved at the values of −35.94, −35.56 and −35.53° for the T2FLS-PSS, ANFIS-PSS and CONV-PSS, respectively. The steady state of rotor angle deviation was achieved at the value of −19.52°. The settling time was achieved at the times of 5.62, 5.89 and 6.44 s for the T2FLS-PSS, ANFIS-PSS and CONV-PSS.

Figure 5(a) and Table 1 are the responses of the rotor speed deviation ($\Delta\omega_7$) when the respective PSS(s) are applied to a large-scale power system. It is shown that the peak overshoot was achieved at the values of −2.17, −3.59 and −5.57×10^{-3} pu for the T2FLS-PSS, ANFIS-PSS and CONV-PSS, respectively. The settling time was obtained at the times of 5.31, 5.83 and 6.55 s for the T2FLS-PSS, ANFIS-PSS and CONV-PSS. It is shown that the responses of the ANFIS-PSS and CONV-PSS are still oscillated. The improvement of the rotor angle deviation ($\Delta\delta_7$) is shown in Figure 5(b) and listed in Table 1. The T2FLS-PSS gave the peak overshoot at the value of −8.48° and the settling time at time of 5.46 s. Meanwhile, the ANFIS-PSS and CONV-PSS gave peak overshoot at the values of −10.25 and −10.23°, respectively. The settling time of the ANFIS-PSS and CONV-PSS was obtained at the times of 6.09 and 6.65 s. Steady state of the rotor angle was achieved at the value of −6.39° for the T2FLS-PSS, and −5.98° for the ANFIS- and CONV-PSS.

From Figure 6(a) and Table 1 we see that peak overshoot of the T2FLS-PSS was achieved at the value of −6.53×10^{-3} pu for the rotor speed deviation ($\Delta\omega_9$). On the other hand, the peak overshoot of the ANFIS-PSS and CONV-PSS were achieved at the values of −6.65 and −7.09×10^{-3} pu. The settling time was obtained at the times of 5.24, 5.74 and 5.98 s, respectively. Furthermore, the responses for the rotor angle deviation ($\Delta\delta_9$) is shown in Figure 6(b) and listed in Table 1.

Simulation result on the First Scenario shows that the T2FLS-PSS is able to improve stability by observing the rotor speed and angle deviation. The T2FLS-PSS gives peak overshoot smaller than the ANFIS/CONV-PSS for both rotor speed and angle. Also, the settling time of the T2FLS-PSS is shorter than the other PSS(s) as well as for the local mode oscillation as well as inter-area mode oscillation.
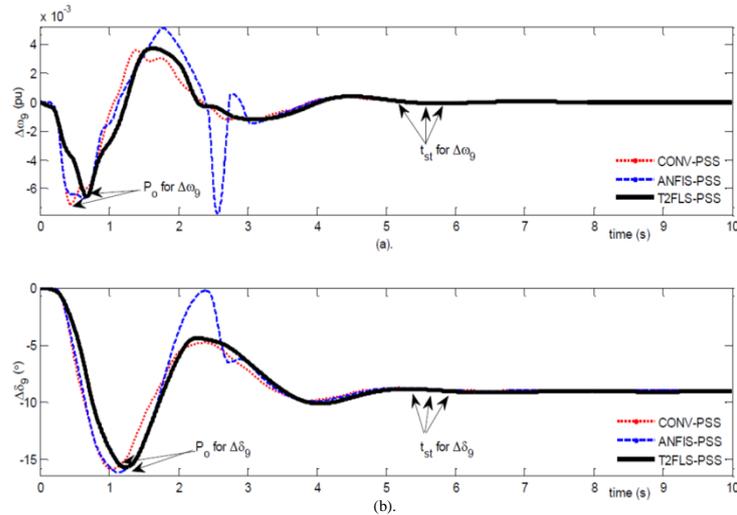
Figure 6. Performance of respective PSS for the (a) $\Delta\omega_9$ and (b) $\Delta\delta_9$ responses

Table 1. Performance of conventional, ANFIS and T2FLS-PSS to improve stability of a LSPS

PSS-type	$\Delta\omega_3$ Peak overshoot [Po] $\times (-10^{-3})$(pu)	Settling time [t_{st}] (s)	$\Delta\delta_3$ Po (°)	[t_{st}] (s)	Ss (°)
CONV-PSS	19.85	5.97	34.53	6.44	
ANFIS-PSS	21.42	5.72	35.56	5.89	19.52
T2FLS-PSS	20.14	5.25	35.94	5.62	
	$\Delta\omega_7$		$\Delta\delta_7$		
CONV-PSS	19.85	5.97	34.53	6.44	
ANFIS-PSS	21.42	5.72	35.56	5.89	19.52
T2FLS-PSS	20.14	5.25	35.94	5.62	
	$\Delta\omega_9$		$\Delta\delta_9$		
CONV-PSS	19.85	5.97	34.53	6.44	
ANFIS-PSS	21.42	5.72	35.56	5.89	19.52
T2FLS-PSS	20.14	5.25	35.94	5.62	

4.2. Evaluation of Respective PSS on Multiple Disturbances

Second Scenario, we also evaluate the respective PSS(s) by forcing 2 (two) mechanical disturbances to the Machine-2 sequentially on 0.08 and 0.09 pu at 0.0 and 8.0 s. Stability improvement of M_3, M_7 and M_9 is observed on dynamic responses of rotor speed and angle deviation. These dynamic responses are shown in Figure 7, Figure 8 and Figure 9. Also, the responses of respective PSS(s) are listed in Table 2.

Figure 7(a) and Table 2 show the dynamic response of the CONV-PSS oscillated with amplitude between −11.23 and 4.60×10⁻³ pu. Then, this amplitude was decreased until the response achieved steady state at time more than 15.0 s. Dynamic response of the ANFIS-PSS also oscillated with amplitude at the values between −9.75 and 3.19×10⁻³ pu. On the other hand, dynamic response of T2FLS-PSS went to first swing and this response increased rapidly to zero (nominal speed). This response was able to achieved steady state at 4.51 and 12.17 s for first and second disturbances, respectively. Peak overshoot of the T2FLS-PSS for the second disturbance was achieved at the value of −6.52×10⁻³ pu. The rotor angle ($\Delta\delta_3$) responses of the all PSS(s) are almost similar. The peak overshoot (P_{o1}) of the T2FLS-PSS, ANFIS-PSS and CONV-PSS were achieved at the values of −21.34, −21.32 and −21.83°, respectively. Next, the rotor angle ($\Delta\delta_3$) achieved P_{o2} at the values of −40.30, −40.32 and −41.23° for the T2FLS-PSS, ANFIS-PSS and CONV-PSS. And, these responses achieved steady state at around −36.04 and −36.20°. This $\Delta\delta_3$ response is shown in Figure 7(b). The performances of the all PSS(s) are listed in Table 2.

Figure 8(a) and Table 2 show the dynamic response of rotor speed deviation ($\Delta\omega_7$) when equipped by the CONV-PSS. This response oscillated with amplitude between −1.81 and 0.65×10⁻³ pu. Then, this amplitude was decreased until the the response achieved steady state at time of more than 15.0 s. Dynamic response of the ANFIS-PSS also oscillated with amplitude at the values between −2.33 and 0.64×10⁻³ pu.

Meanwhile, the dynamic response of T2FLS-PSS was not oscillated and this response was able to achieved steady state at 4.48 and 12.15 s for first and second disturbances, respectively. Peak overshoot of the T2FLS-PSS for the second disturbance P_{o2} was achieved at the value of -1.12×10^{-3} pu.

The rotor angle ($\Delta\delta_7$) for the T2FLS-PSS, ANFIS-PSS and CONV-PSS achieved the peak overshoot P_{o1} at the value of -6.68, -6.38 and $-6.41°$. Furthermore, the rotor angle P_{o2} was achieved at the values of -12.45, -12.10 and $-12.27°$, respectively. And, the steady state was achieved at around -11.46 and $-11.06°$ for the all PSS. The $\Delta\delta_7$ response is shown in Figure 8(b) and listed in Table 2.
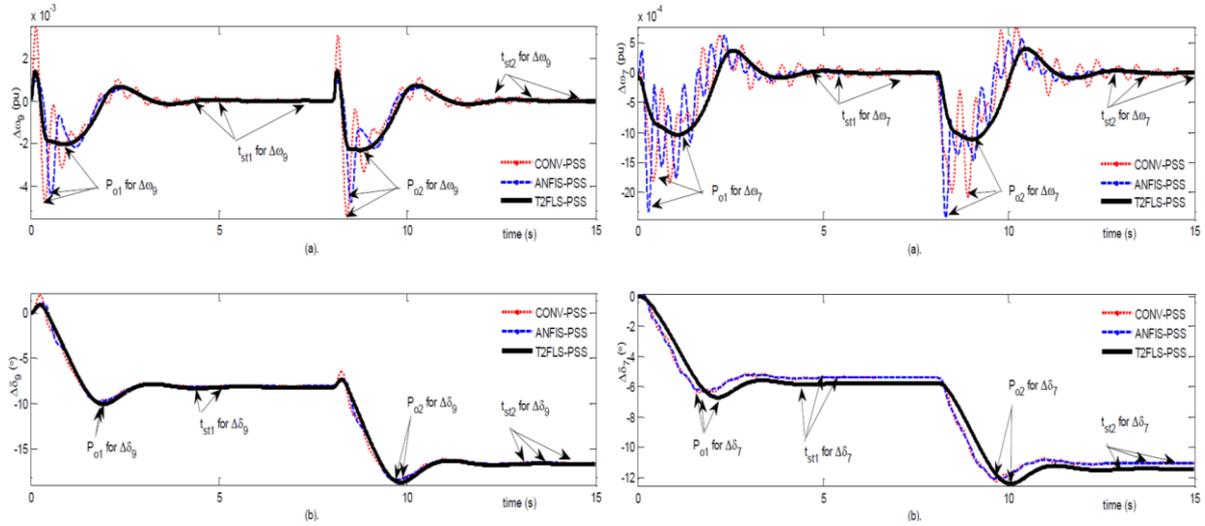

Figure 7. Responses of the (a) $\Delta\omega_3$ and (b) $\Delta\delta_3$ forced by multiple disturbances

Figure 8. Performance of the respective PSS on (a) $\Delta\omega_7$ and (b) $\Delta\delta_7$

Dynamic responses of ($\Delta\omega_9$) for the respective PSS are shown in Figure 9(a) and Table 2. Oscillation occurred on the CONV-PSS response with amplitude between -4.74 and 3.42×10^{-3} pu. This response was decreased and achieved the settling time at more than 8 s (t_{st1}) and 15 s (t_{st2}), for first and second disturbances, respectively. The oscillation also appeared on the ANFIS-PSS response with amplitude at the values between -4.46 and 1.13×10^{-3} pu. But, the amplitude of the ANFIS-PSS response is less than the amplitude of the CONV-PSS response. Moreover, the rotor speed ($\Delta\omega_9$) that system equipped by the T2FLS-PSS achieved peak overshoot at the values of -2.02 (P_{o1}) and -2.30×10^{-3} (P_{o2}) pu. Response of T2FLS-PSS is better than the other PSS(s).
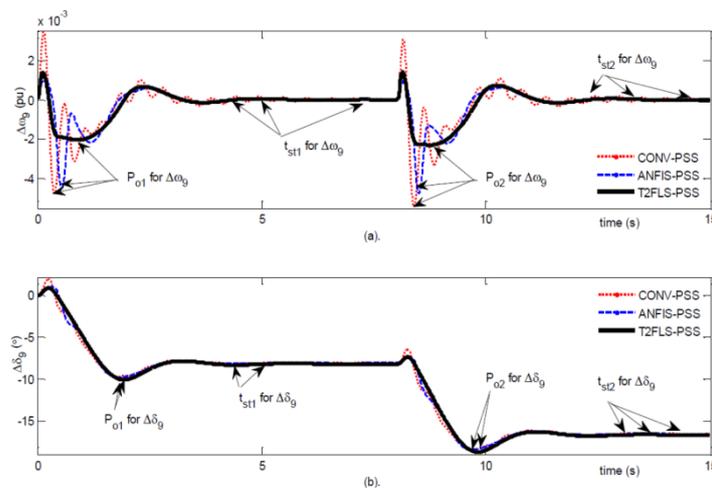

Figure 9. Enhancement stability of the (a) $\Delta\omega_9$ and (b) $\Delta\delta_9$ by using the T2FLS-PSS

The rotor angle ($\Delta\delta_9$) for the T2FLS-PSS, ANFIS-PSS and CONV-PSS achieved the peak overshoot (P_{o1}) at the values of −10.04, −9.75 and −9.71°. Again, when the second disturbance was disturbed, the peak overshoot of the T2FLS-PSS, ANFIS-PSS and CONV-PSS was achieved at the values of −18.68, −18.41 and −18.43°, respectively. Settling time (t_{st1}) for the T2FLS-PSS, ANFIS-PSS and CONV-PSS was achieved at the times of 4.24, 4.32 and 5.44 s. Next, the settling time (t_{st2}) was achieved at the times of 12.11, 12.29 and 13.07 s. Steady state (S_{s1}) was achieved at the value of −5.78° for the T2FLS-PSS, and at the value of −5.39° for the ANFIS-PSS and CONV-PSS. Finally, the steady state (S_{s2}) was achieved at values of −16.65, −16.51 and −16.50° for the T2FLS-PSS, ANFIS-PSS and CONV-PSS, respectively. The performance of respective PSS(s) on ($\Delta\delta_9$) response are shown in Figure 9(b) and Table 2. The simulation results of this paper are in-line with the simulation results in [16] that the settling time of the PSS responses in multimachine system are around 5.0 s.

Table 2. Performance of respective PSS on second disturbance at 0.09 pu and 8.0 s

PSS-type	$\Delta\omega_3$				$\Delta\delta_3$					
	P_{o1}	P_{o2}	t_{st1}	t_{st2}	P_{o1}	P_{o2}	t_{st1}	t_{st2}	S_{s1}	S_{s2}
	$\times[-10^{-3}]$ (pu)		(s)		−(°)		(s)		−(°)	
CONV-PSS	10.12	11.23	>8.0	>15.0	21.83	41.23	7.8	14.9	17.71	36.2
ANFIS-PSS	8.03	9.75	4.85	12.49	21.26	40.32	4.82	12.47	17.65	36.12
T2FLS-PSS	6.52	7.86	4.51	12.17	21.34	40.30	4.79	12.36	17.52	36.04
	$\Delta\omega_7$				$\Delta\delta_7$					
CONV-PSS	1.81	2.09	>8.0	>15.0	6.41	12.27	5.43	13.15	5.39	11.06
ANFIS-PSS	2.33	2.43	4.81	12.47	6.38	12.10	4.51	12.38	5.39	11.06
T2FLS-PSS	1.01	1.12	4.48	12.15	6.68	12.45	4.32	12.14	5.78	11.46
	$\Delta\omega_9$				$\Delta\delta_9$					
CONV-PSS	4.74	5.45	>8.0	>15.0	9.71	18.43	5.41	13.07	5.39	16.50
ANFIS-PSS	4.46	4.74	4.75	12.39	9.75	18.61	4.32	12.29	5.39	16.51
T2FLS-PSS	2.02	2.3	4.36	11.97	10.04	18.68	4.24	12.11	5.78	16.65

5. CONCLUSION

The coordination of ANFIS-PSS and T2FLS-PSS are evaluated on a large-scale power system (LSPS). The design of PSS based on ANFIS and T2FLS are also explored in-depth in this research. On designing process, the ANFIS-PSS parameters are obtained automatically through learning stage. All the data that used in the learning stage are obtained by simulating the LSPS equipped by conventional PSS (CONV-PSS) with varied load capacity. The learning processes are conducted in off-line mode. Meanwhile, the T2FLS parameters are determined by design based on the knowledge of the designer. The proposed PSS(s) are tested by using two scenarios in order to validity of the model. In First Scenario, the system is forcing by a single mechanical disturbance on the Machine-2. The simulation results are observed on the rotor speed and angle of the Machine-3 (M_3) for mode local oscillation, and Machine-7 (M_7) and Machine-9 (M_9) for mode inter-area oscillation. The simulation results are as follows: The settling time of the rotor speed ($\Delta\omega_3$) and angle $\Delta\delta_3$ are obtained at the times of 5.25 and 5.62 s, respectively, for T2FLS-PSS. The steady state values for the $\Delta\delta_3$ responses of all the PSS(s) are obtained at −19.52°. When multiple disturbances are forced to the system, responses of the T2FLS-PSS are as follows: The settling time are obtained at 4.51 s (t_{st1}) and 12.17 s (t_{st2}) for the $\Delta\delta_3$. The settling time are obtained at 4.79 s (t_{st1}) and 12.36 s (t_{st2}) for the $\Delta\delta_3$. The steady state values are obtained at −17.52° (S_{s1}) and −36.04° (S_{s2}). The evaluation on inter-area mode oscillation (Area II and III) is obtained as follows: The ($\Delta\omega_7$) and $\Delta\delta_7$ are obtained at the times of 5.31 and 5.46 s for the T2FLS-PSS. The steady state values for the $\Delta\delta_7$ responses of the T2FLS-PSS is obtained at 6.39°. The ($\Delta\omega_9$) and $\Delta\delta_9$ are obtained at the times of 5.24 and 5.43 s for the T2FLS-PSS. The evaluation is also conducted on multiple disturbances. In this scenario, responses of the CONV-PSS and ANFIS-PSS oscillated in a few second. Meanwhile, the T2FLS response for the ($\Delta\delta_3$) achieved the settling time at times of 4.70 and 12.36 s for the first and second disturbances, respectively. The peak overshoot (P_{o1} and P_{o2}) are achieved at the values of −6.52 and −7.86× 10^{-3} pu. It is concluded that the T2FLS-PSS gives better responses than the other PSS. Where, peak overshoot of the T2FLS-PSS less than the other PSS and the settling time also shorter than the other PSS.

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