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Stability Improvement of Single Machine using ANFIS-PSS Based on Feedback-linearization

I Made Ginarsa[1], Osea Zebua[2]
[1] Dept. of Electrical Engineering, Mataram University
Jln. Majapahit No. 62 Mataram, Telp/fax+62 370 636755
[2] Dept. of Electrical Engineering, University of Lampung
Jln. Prof. SumantriBrojonegoro No. 1, Bandar Lampung, Telp. +62 721701609
*Corresponding author, e-mail: [1]kadekgin@yahoo.com; [2]oseaz89@yahoo.com

Abstract

Electrical power system (EPS) operation always follows load changes which occur within time. Load changes and disturbances cause EPS operation to find a new balance point and before can reach the new balance point, the rotor speed will swing around its synchronous speed. This phenomenon causes the stability of the EPS operation decrease significantly, moreover, when the disturbance is large the machine tend to become unstable. To overcome this problem, it is necessary to add a power system stabilizer (PSS). This research proposes ANFIS-PSS based on feedback-linearization to stabilize the EPS operation. Feedback-linearization is a nonlinear control technique which feedback and limits several outputs in order to make the nonlinear system acts as a linear system. Data from conventional PSS is used to train and to update ANFIS-PSS parameters. Simulation results show an improvement of the stability of single machine model such as decreasing in maximum magnitude of rotor speedat the value of 0.466 rad/s and to reduce the time settling to 5.6 s.

Keywords*: stability, PSS, ANFIS, feedback-linearization, settling time reducing*

1. Introduction

Electric power systems have intrisically naturaland should be modelled using a nonlineardifferential equation.Conventional linear control has limited ability, so it is able to stabilize a plant due to dynamic (small) disturbance and work with one point operation only [1].Some efforts have been done to reduce the rotor oscillation in power systems by using power system stabilizer (PSS) based on neural network (NN), such as,heuristic-dynamic-programming [2], adaptive NN [3] and recurrent NN [4].Nonlinear control scheme was applied to control steam turbine valve in a multimachine power system using the geometrical differential method [5]. So, stabilization of a multimachine power system via excitation control using decentralized feedback-linearization was able to reduce rotor oscillation against dynamic and transient disturbances. Input signal control was observed by local measurement only [6]. PSS design using feedback-linearization in nonlinear power system model by considering the magnitude limit of control signal have been done by Liu et al. [7]. Robust control technique via Lyapunov method was used to improve the stability of a nonlinear power system when the power system was forced by heavily disturbances [8].

ANFIS algorithm is a method which their parameters are obtained automatically by learning process via data training. In recent years, some ANFIS algorithm have been widely used to control the chaos and voltage collapse in power system. Combination of composite controller-static var compensator based on ANFIS algorithm have been used to suppress chaos, voltage collapse, and also to add loading margin in a power system [9]-[11]. Furthermore, by applying a PID-loop based ANFIS to the systemsthat was obtained the improvement of transient voltage response [12]-[13]. Design and digital simulation of ANFIS-PSS with a real power deviation was used as an input for the ANFIS-PSS.It was obtained that the ANFIS-PSS was able to damp thelocal and inter-area oscillations [14]. Also, the first order Sugeno model has been used to design ANFIS-PSS andthis model can be able to damp local and inter-area oscillations [15]. Damping of rotor oscillation has been done by using layered recurrent network-based PID-SVC controller [16]. SVC controlled by NN was used to enhance dynamic stability of power system [17].

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This paper is organized as follows: Single machine model connected to infinite bus is explained in Section 2. ANFIS power system stabilizer based on control nonlinear via feedback-linearization method is detailed in Section 3. Simulation result and analysis are described in Section 4. Finally, the conclusion is provided in the last section.

2. Single Machine Model Connected to Infinite Bus

A single machine model which used in this research consists of turbine, generator (machine), excitation system (exciter), automatic voltage regulator (AVR) and external line connected to infinite bus [18]. This model is illustrated in Figure 1 and its parameters are listed in Table 1. A synchronous generator is modeled by using a voltage (E'_{q0}) behind a direct reactance (x'_d). Steam or gas turbine function convertsthermal energy to mechanical energy or torque (T_m). Synchronous generator produces terminal voltage ($V\angle\theta$)at a bus machine through excitation system. Single machine connected to infinite bus is expressed by formula Eqs.(1)-(5).

$$\dot{\delta} = \omega - \omega_0 \quad (1)$$

$$\dot{\omega} = \frac{\omega_0}{2H}\left[T_m - E'_q I_q - \left(x_q - x'_d\right) I_d I_q - D_{fw}(\omega - \omega_0)\right] \quad (2)$$

$$\dot{E}'_q = \frac{1}{t'_{d0}}\left[-E'_q - \left(x_q - x'_d\right) I_d + E_{fd}\right] \quad (3)$$

$$\dot{E}_{fd} = \frac{1}{t_e}\left[-E_{fd} + V_r\right] \quad (4)$$

$$\dot{V}_r = \frac{1}{t_a}\left[-V_r + K_A\left(V_{ref} - V_t - V_{pss}\right)\right] \quad (5)$$

where T_m, δ, ω, ω_0, D and M are the mechanical torque, rotor angle, rotor speed, synchrounous speed, damping constant and inertia constant, respectively.Thevariabels I_d, I_q and V_t are constrained by Eqs. (6)-(8), respectively.

$$r_e I_d + \left(x_q - x_e\right) I_q + V_0 \sin(\delta - \theta_0) = 0 \quad (6)$$

$$r_e I_q + (x'_d - x_e) I_d - E'_q + V_0 \cos(\delta - \theta_0) = 0 \quad (7)$$

$$V_t = \sqrt{V_d^2 + V_q^2} \quad (8)$$

Table 1. Power System Parameters

x_d	x'_d	x_q	t'_{d0}
0.8958	0.1198	0.8645	6.0
H	t_a	K_A	ω_0
6.0	0.01	20.0	377
Dfw	t_e	r_e	x_e
0.0125	0.314	0.025	0.085

$$V_d = r_e I_d - x_e I_q + V_0 \sin(\delta - \theta_0) \quad (9)$$

$$V_q = r_e I_q + x_e I_d + V_0 \cos(\delta - \theta_0) \quad (10)$$

where V_d, V_q and V_t are the direct, quadrature and terminal voltages, repectively. While, I_d and I_q are the direct and quadrature currents.

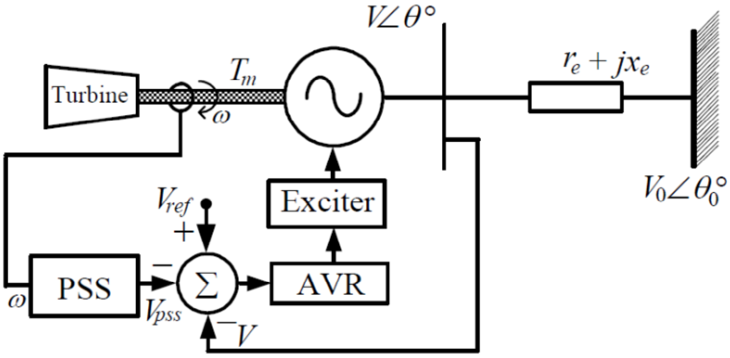

Figure 1. Single-machine model equipped by PSS.

3. ANFIS-PSS Based on Feedback-linearization Design

3.1. Feedback-linearization method

Nonlinear control technique feedback-linearization method is a technical procedure that state feedback of a nonlinear system, where some outputs of the system are bounded (constrained). This method made the system behave as a linear system [19]. When some of variables such as I_d, I_q and V_t, are not state variables, a transformationis needed to make that variables became state variables. Single machine model that expressed by variables in Eqs. (2)-(5) is transformed into the model that expressed by variables in Eqs. (11)-(14).Part from this, the state variable (δ) in Eq. (1) is still the same.

$$\dot{\omega} = k_6 \sin^2 \delta_m + k_7 \cos^2 \delta_m + k_8 \sin \delta_m \cos \delta_m + k_{13} + k_9 \sin \delta_m E_q^{'} + k_{10} \cos \delta_m E_q^{'} + k_{11} E_q^{'2} + k_{12}\omega \quad (11)$$

$$\dot{E_q^{'}} = -k_{14} E_q^{'} + k_{16} \sin \delta_m + k_{17} E_q^{'} + k_{18} \cos \delta_m + k_{14} E_{fd} \quad (12)$$

$$\dot{E_{fd}} = k_{19} E_{fd} - k_{19} V_r \quad (13)$$

$$\dot{V_r} = k_{27} V_r + k_{28} V_{ref} - k_{28} V_t + k_{28} V_{pss} \quad (14)$$

where $\delta_m = (\delta - \theta_0)$.In addition, definition of constants from k_1 to k_{28} are given in Appendix B.

3.2 Linearization processes of input-output controller

The single machine which is connected to theinfinite bus is a single input-single output (SISO) nonlinear control problem. In this research, speed rotor (ω) variable is used as an object control.By defining $e = \omega - \omega_0$, the control objective is regulated toward zero value. To obtain the rotor speed deviation (e) that connect to control signal (u) it isrequired to differentiate $e$several times until the control signal (u) is appeared. Derivative processes are shown as follows:

$$\dot{e} = \dot{\omega} \quad (15)$$

$$\ddot{e} = \ddot{\omega} \quad (16)$$

$$\dddot{e} = \dddot{\omega} \quad (17)$$

$$e^{(4)} = \omega^{(4)} = f(X) + g(X) \times u \quad (18)$$

Derivative process of the error from $\dot{e}(\dot{\omega})$to $e^{(4)} = \omega^{(4)}$aregiven in Appendix A. Variabel $X$is initial state variable which consists ofrotor angle (δ),rotor speed (ω),quadrature axis voltage (E'_q),field voltage (E_{fd}) and output voltage of AVR (V_r), respectively. The state variabel $\omega$is chosen as acontrol objective. In this case, the control signal (u)appeared at the fourth derivative of ω, ($\omega^{(4)}$).By this process the system became afourth-order feedback-linearized system. Since uncontrolled state variabel δ satisfy$\dot{\delta} = \omega - \omega_0$, state variable $\delta$is bounded whenstate variable ω was able to stabilize ω_0.Next step is to define reference signals (x_d) and error signals (e).

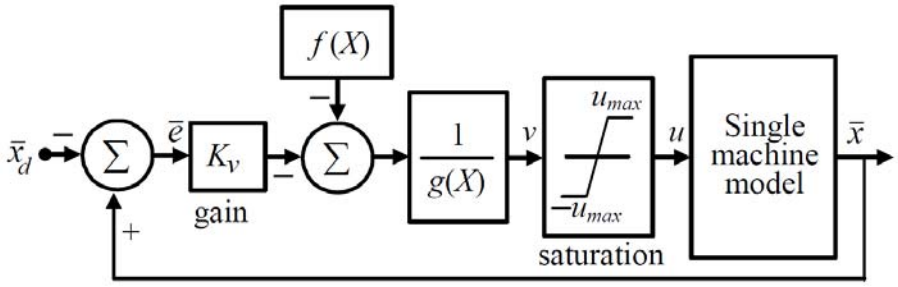

Figure 2. Feedback-linearizationcontrol technique that was implemented in single machine model.

$$x_d = [x_{d1} \quad x_{d2} x_{d3} \quad x_{d4}]^T = [\omega_0 \quad \dot{\omega}_0 \ddot{\omega}_0 \quad \dddot{\omega}_0]^T \tag{19}$$

$$\bar{e} = \bar{x} - \bar{x}_d = [e_1 \quad e_2 e_3 \quad e_4]^T \tag{20}$$

where T is vector transpose. The dynamics of the system are expressed as follows:

$$\dot{e}_1 = e_2 (21); \dot{e}_2 = e_3 (22); \quad \dot{e}_3 = e_4 \tag{23}$$

$$\dot{e}_4 = f(X) + g(X) \times u - \dot{x}_{d4} \tag{24}$$

In this research, the line frequency (f) is 60 Hz. So, $\omega_0$is a constant value at 2×π×60 = 377 rad/s. Therefore, all of its derivatives have zero values. Ideal control signal $v$was chosen as follow:

$$v = \frac{1}{g(X)}[-K_v \times \bar{e} \quad -f(X)] \tag{25}$$

Where K_v is the gain vector. $K_v = [a_4 \quad a_3 \, a_2 \quad a_1]$, where a_1, a_2, a_3 and a_4 are the parameters of the gain vector. The parameters a_1, a_2, a_3 and $a_4$are chosen properly to make the closed-loop system stable. Then, theclosed-loop dynamical system was transformed into a linear system without magnitude constraint (u = v).

$$\dot{\bar{e}} = K_v \times \bar{e} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -a_4 & -a_3 & -a_2 & -a_1 \end{bmatrix} \times \bar{e} \tag{26}$$

By choosing the parameters a_1, a_2, a_3 and $a_4$properly, the system in Eq. (26) tendsto asymptotically stable (e→0). Since the actual control signal is a subjec to magnitude contraints, the applied control signal (u) is given by

$$u = \begin{cases} v & while\ |v| \le u_{max} \\ u_{max}\, sign(v) & while\ |v| > u_{max} \end{cases} \tag{27}$$

Where the $u_{max}$is the maximumallowed control signal magnitude.

3.3. ANFIS-PSS Design Processes

An ANFIS-PSS was designed using ideal control signal (v)and rotor speed as inputs, and control signal from PSS as the output. Each inputs of the ANFIS-PSS have five membership functions. The membership function that used to state each inputs are Gauss type 2 membership function. Each inputs used five linguistic variabels such as: negative high (NH), negative low (NL), zero (ZE), positive low (PL) and positive high (PH) to express the value of the input signal. Fuzzy model Takagi-Sugeno (T-S) is used to implement the fuzzy inference system.The output of the ANFIS PSS is a signal control (V_{pss}) and 25 rules with linear membership function are used to implement the output signal.

Learning stages are done by using off-line method with 4000 data matrix input-outputs. In this stage the data is structured in matrix form as [$v\omega V_{pss}$], where v, ω , are the input signal control ideal and input rotor speed, respectively. V_{pss} is the output control signal from ANFIS-PSS.The proposed ANFIS-PSSis applied to a single machine connected to infinite bus as shown in Figure 3.Architecture and input-output surface control of ANFIS-PSS are shown in Figure 4 (a) and 4 (b), respectively.

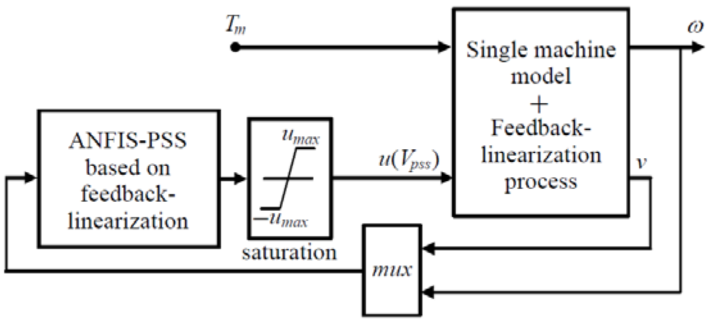

Figure 3. Implementation of the ANFIS-PSS to improve stability of single machine.

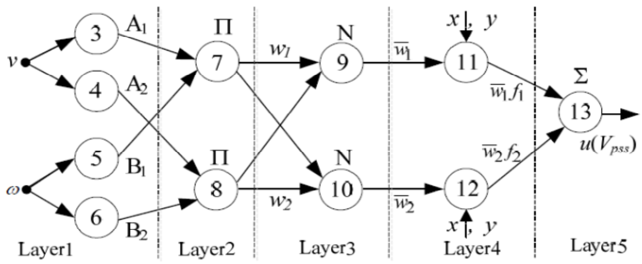

Figure4 (a). Architecture of fuzzy Sugeno with two input (v,ω) and one output (V_{pss}).

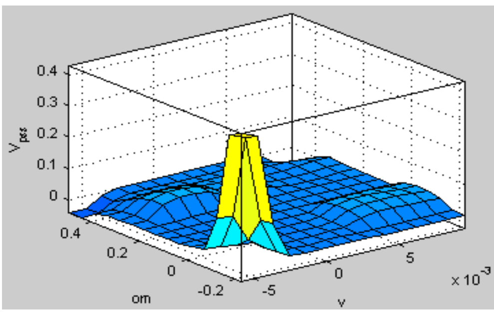

Figure 4 (b). Input-output surface control of ANFIS-PSS

4. Results and Analysis

To demonstrate the performance of the ANFIS-PSS to improve stability in a single machine nonlinear model,the system isimplemented and examined using Matlab/Simulink 7.9.0.529 [20] on an Intel Core 2 Duo E6550 233 GHz PC computer.

The simulation was performed by forcing the single machine with additional torque (T_m) at the value of 0.1 pu and at time of 100 ms. The responses were observed in speed rotor (ω) and rotor angle (δ). From Figure 5, it is shown that the maximum magnitude (M_{max}) of the rotor speed was achieved at the value of 0.555 rad/s for the single machine without equipped by the PSS. Meanwhile, the maximum magnitude occured (t_{max}) at time of 0.4 s. Furthermore, this response was damped, so its response achieved the steady state with settling time of 27.5 s. From the Figure 5 we can see that the response of the single machine without equipped by PSS very oscillate.This oscillation can be occured because the system naturally has insuffiction damping component to damp the rotor oscillation when the system is disturbed. Next, ANFIS-PSS is proposed to produce an additional signal. This additional signal is used to modulate the automatic voltage regulator (AVR) to produce damping torque component through the exciter system. So, the damping torque component is used to damp the rotor oscillation. And, the response of the proposed controller is also compared to the response of conventional PSS (CPSS) in order to valid of the simulation result.

Maximum magnitude, time of the maximum magnitude occurred and settling time ofthe CPSS response was achieved at the value of 0.492 rad/s, time of 0.37 s and 7.89 s, respectively. Meanwhile, the response of the proposed controller was achieved at the value of 0.466 rad/s, time of 0.33 s and 5.6 s, for the maximum magnitude, time of the maximum magnitude occured and settling time, respectively.It is shown that the proposed controller is able to reduce the maximum magnitude and settling time of the rotor speed response. The response of the proposed controller is better than the other controllers.

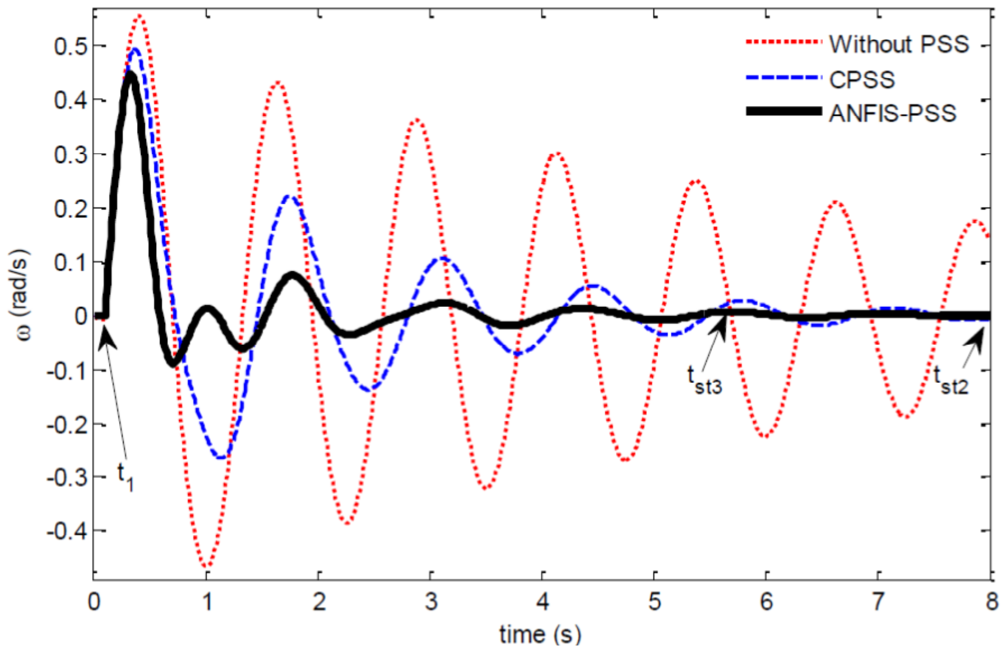

Figure 5. Responses of single machine without PSS, conventional-PSS, and ANFIS-PSS is compared to obtain their respective performances.

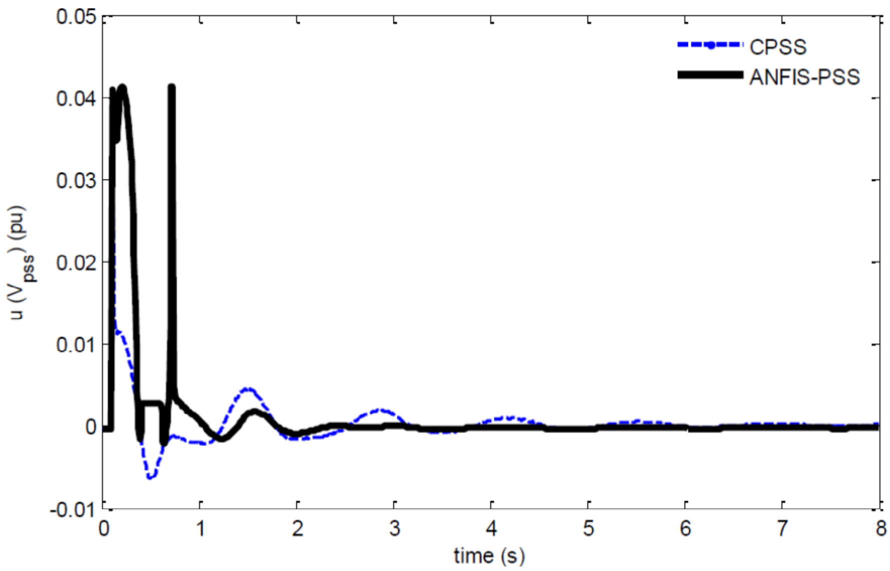

Figure 6. Control signals produced by the conventional PSS and ANFIS-PSS.

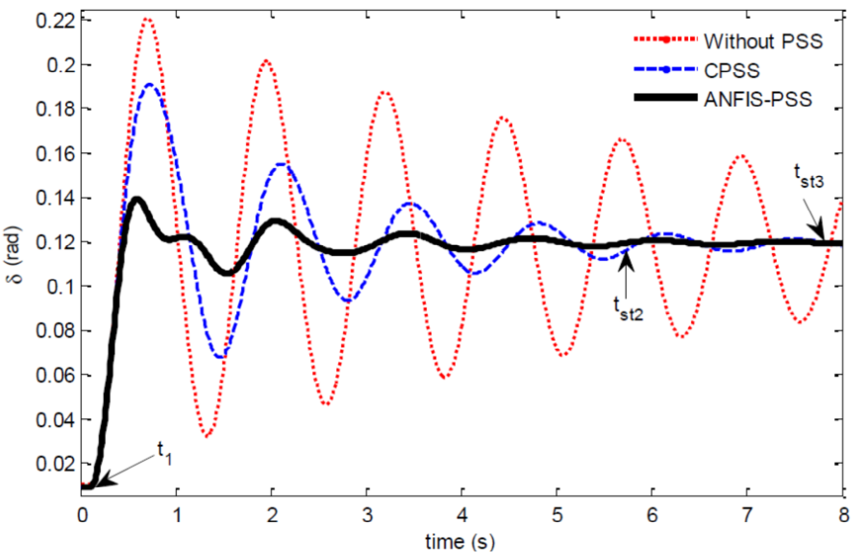

Figure 7. Responses of rotor angle for respective controllers.

Figure 6 shows the signal control pattern ($u(V_{pss})$) from CPSS and the proposed PSS. This signal was used to modulate AVR in the excitation system.It is shown that the maximum magnitude ($u(V_{pss})$) of the signal control was less than the magnitude constraint (u_{maks} = 0.5 pu). The control signal that produced by the PSS is bounded.By this result it is guaranteed that the system is stable.

The response of the rotor angle is shown in Figure 7. Figure 7 shows the maximum magnitude of the CPSS and proposed PSS was achieved at the values of 0.191 and 0.1396 rad, respectively. In addition, the settling time of the CPSS and proposed PSS was achieved at the times of 7.97 and 5.6 s, respectively.Meanwhile, the response of the single machine without PSS oscillated in more than 28 s and the maximum magnitude was more than 0.22 rad. From the rotor angle response, we see that the proposed PSS gives better response than the other controller.

5. Conclusion

Power systems always operate in a balance condition between power demand and supply. Balancing operation of power systems can be disturbed by load or structure changes. When the operationisunbalance, this condition causes the rotor speed reach oscillation mode. In this research ANFIS-PSS based on feedback-linearization is proposed to improve stability of rotor oscillation of single machine.Gauss type 2 membership function is used to implement respective ANFIS parameters. The ANFIS parameters are obtained automatically by using learning processes. The simulation shows that the proposed PSS is able to improve stability of single machine where the settling time is achieved at the times of 5.6 and 5.59s for the rotor speed and rotor angle responses, respectively. Finally, the maximum magnitude of the proposed PSS is obtained at the values of 0.466 and 0.1396 rad/s for the rotor speed and rotor angle.

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Abbreviation and Symbol

ANFIS	Adaptive neuro-fuzzy inference system	H	Inertia constant
AVR	Automatic voltage regulator	t'_{d0}	Direct-axis time constant
PSS	Power system stabilizer	θ_0	Initial rotor angle
CPSS	Conventional PSS	e	Error signal
r_e	network resistance	u (V_{pss})	Control signal
x_e	Network reactance	v	Ideal control s

Appendix **A:**
Feedback-linearization
For the sake of simplicity the variabel $\delta_m = \beta$

$$V_t = \sqrt{k_{21}\sin^2\beta + k_{22}\cos^2\beta + k_{23}{E_q'}^2 + k_{24}\sin\beta\, E_q' + k_{25}\cos\beta\, E_q' + k_{26}\sin\beta\cos\beta + {V_0}^2} \quad \text{(A1)}$$

$$\begin{gathered}\ddot{e} = \ddot{\omega} = (k_6 - k_7)\sin(2\beta)\dot{\delta} + k_8\cos(2\beta)\dot{\delta} + 2k_{11}E_q'\dot{E}_q' \\ + k_{12}\dot{\omega} + \left(k_9E_q'\dot{\delta} + k_{10}\dot{E}_q'\right)\cos\beta + \left(k_9\dot{E}_q' - k_{10}E_q'\dot{\delta}\right)\sin\beta\end{gathered} \quad \text{(A2)}$$

$$\begin{gathered}\dddot{e} = \dddot{\omega} = \left[2(k_6 - k_7)\dot{\delta}^2 + k_8\dot{\omega}\right]\cos(2\beta) + \left[(k_6 - k_7)\dot{\omega} - 2k_8\dot{\delta}^2\right]\sin(2\beta) \\ -(k_9\cos\beta + k_{10}\sin\beta)\left[E_q'\dot{\delta}^2 + k_{14}\dot{E}_{fd} - (k_{14} - k_{14})\dot{E}_q' - (k_{16}\cos\beta + k_{18}\sin\beta)\dot{\delta}\right] \\ +(k_{16}\cos\beta - k_{18}\sin\beta)2k_{11}E_q'\dot{\delta} + k_{12}\ddot{\omega} + 2k_{11}{E_q'}^2 + 2k_{11}k_{14}E_q'\dot{E}_{fd} - 2k_{11}(k_{14} - k_{17})E_q'\dot{E}_q'\end{gathered} \quad \text{(A3)}$$

$$\begin{gathered}f(X) = \sin(2\beta)\left[(k_7 - k_6)\left(2\dot{\delta}^3 - \ddot{\omega}\right) - 6k_8\dot{\delta}\dot{\omega}\right] - \cos(2\beta)\left[6(k_7 - k_6)\dot{\delta}\dot{\omega} + 4k_8\dot{\delta}^3 - k_8\ddot{\omega}\right] \\ +(k_9\cos\beta - k_{10}\sin\beta)\left[2\ddot{E}_q'\dot{\delta} + 3\dot{E}_q'\dot{\omega} + 2k_{11}k_{14}\dot{E}_q'\dot{E}_{fd} - 2k_{11}(k_{14} - k_{17}){\dot{E}_q'}^2\right] \\ -(k_9\sin\beta + k_{10}\cos\beta)\times \\ \left[3\dot{E}_q'\dot{\delta}^2 + 3E_q'\dot{\delta}\dot{\omega} + (k_{14} - k_{17})\ddot{E}_q' - k_{14}k_{19}\left(\dot{E}_{fd} - k_{27}V_r + k_{28}V_t - k_{28}V_{ref}\right)\right] \\ (k_{16}\cos\beta - k_{18}\sin\beta)\left\{(k_9\cos\beta - k_{10}\sin\beta)\dot{\delta}^2\right. \\ \left.+\left[(k_9\sin\beta + k_{10}\cos\beta) + 2k_{11}E_q'\right]\dot{\omega} + 2k_{11}\dot{E}_q'\dot{\delta}\right\} \\ -\left(k_9\sin\beta + k_{10}\cos\beta + 2k_{11}E_q'\right)(k_{16}\sin\beta + k_{18}\cos\beta)\dot{\delta}^2 \\ +2k_{11}\dot{E}_q'\left[k_{14}\dot{E}_{fd} - (k_{14} - k_{17})\dot{E}_q'\right] + 2\left[k_{11}(k_{17} - k_{14}) + 2k_{11}\right]\dot{E}_q'\ddot{E}_q' \\ +k_{12}\dddot{\omega} + 2k_{11}k_{14}k_{19}E_q'\left(\dot{E}_{fd} - k_{27}V_r + k_{28}V_t - k_{28}V_{ref}\right)\end{gathered} \quad \text{(A4)}$$

$$g(X) = k_{14}k_{19}k_{28}\left(k_9\sin\alpha + k_{10}\cos\alpha + 2k_{11}E_q'\right) \quad \text{(A5)}$$

$$\ddot{E}_q' = -k_{14}\dot{E}_q' + k_{16}\,\dot{\delta}\cos\beta + k_{17}\dot{E}_q' + k_{18}\,\dot{\delta}\sin\beta + k_{14}\dot{E}_{fd} \quad \text{(A6)}$$

Appendix B:
Constant calculationk_1- k_{28}

$$k_1 = \frac{r_e}{r_e^2 + \left(x_d' + x_e\right)(x_q + x_e)}; \quad k_2 = \frac{x_q + x_e}{R_e^2 + \left(x_d' + x_e\right)(x_q + x_e)}; \quad k_3 = \frac{-x_d' - x_e}{r_e^2 + \left(x_d' + x_e\right)(x_q + x_e)}; \quad k_4 = -x_q - x_d'; \quad k_5 = \frac{\omega_0}{2H};$$

$k_6 = k_1k_3k_4k_5V_0^2$; $k_7 = k_1k_2k_4k_5V_0^2$; $k_8 = (k_1^2 + k_2k_3)k_4k_5V_0^2$; $k_9 = [k_3 - (k_1^2 + k_2k_3)k_4]k_5V_0^2$;

$k_{10} = (k_1 - 2k_1k_2k_4)k_5V_0^2$; $k_{11} = (k_1k_2k_4 - k_1)k_5$; $k_{12} = -D_{fw}k_5$;

$k_{14} = \frac{1}{T'_{d0}}$;$k_{13} = k_5(T_m + -D_{fw}\omega_0)$;$k_{15} = -x_d + x'_d$; $k_{16} = -k_1k_{14}k_{15}V_0$; $k_{17} = k_2k_{14}k_{15}$;

$k_{18} = -k_2k_{14}k_{15}V_0$; $k_{19} = -\frac{1}{T_e}$; $k_{20} = r_e^2 + x_e^2$;$k_{21} = (k_1^2 + k_3^2)k_{20}V_0^2 - 2k_1R_eV_0^2 + 2k_3x_eV_0^2$;

$k_{22} = (k_1^2 + k_2^2)k_{20}V_0^2 - 2k_2X_eV_0^2 - 2k_1r_eV_0^2$; $k_{23} = (k_1^2 + k_2^2)k_{20}$;

$k_{24} = -2(k_1k_2 + k_1k_3)k_{20}V_0 + 2k_2r_eV_0 - 2k_1x_eV_0$; $k_{25} = -(k_1^2 + k_2^2)k_{20}V_0 + 2k_2x_eV_0 + 2k_1r_eV_0$;

$k_{26} = 2(k_2 + k_3)k_1k_{20}V_0^2 - 2(k_2 + k_3)r_eV_0^2$; $k_{27} = -\frac{1}{T_a}$; $k_{28} = -\frac{K_A}{T_a}$;