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Multi-Machine Power System Stabilizer Using Type-2 Adaptive Fuzzy Sliding Mode Controller

E Nechadi[1, 2] and MN Harmas[1, 2]

[1]*Department of Electrical Engineering, Ferhat Abbas University of Sétif, Algeria*
[2] *CReSTIC Laboratory, University of Reims Champagne Ardennes, France*
nechadiamira@yahoo.fr

ABSTRACT

This paper presents a novel system stabilizer based on type-2 adaptive fuzzy sliding mode approach without reaching phase and chattering for a nonlinear power system. Low frequency oscillations of small magnitude linked with the electromechanical models in power systems, often persevere for long periods and may in some cases drastically hinders power transfer capability. These oscillations may occur locally or inter-power areas, due to in a large part to the difference in generators inertia constants of weakly linked power areas. Robustness of power availability can therefore be jeopardized. To help prevent these oscillations from limiting power flow, we present a new sliding mode based power system stabilizer with a sliding surface such that the system is always on the sliding surface and hence improve the system robustness. Furthermore, to account for rapidly changing operating conditions we use two adaptive Type-2 fuzzy systems to approximate the unknown power system nonlinear dynamics. To overcome the presence of chattering, we use a modified control signal. Stability is insured through Lyapunov synthesis. Severe operating conditions are used in a simulation study to test the validity and effectiveness of the proposed method which indicates good performance and satisfactory transient dynamic behaviour. A multi-machine power system is used to demonstrate the performance of the proposed controller and its superiority over conventional stabilizers used in the literature.

Key words: Two machine power system stabilizer (PSS), novel sliding mode surface, type-2 adaptive fuzzy system, Lyapounov

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INTRODUCTION

A power system must be modelled as a nonlinear system for large disturbances. Power system stability has been generally defined according to system operating conditions. Transient stability has been an utmost concern for many power specialists for it is related to synchronism maintaining between generators in the case of a severe disturbance [1-4]. The use of high performance excitation systems is essential for maintaining steady state and transient stability of modern synchronous generators and provides fast terminal voltage control [4]. However, these fast acting exciters with high gains can contribute to oscillatory instability in the power system. This type of instability is characterized by low frequency oscillations, which can persist or even grow in magnitude [5]. Avoiding this counterproductive effect, supplementary stabilizing signals have been proposed in the excitation systems through lead-lag power system stabilizers [6-7]. The computation of the fixed parameters of these stabilizers is based on the linearized model of the power system around a nominal operating point [5]. Nevertheless, if the parameters of the stabilizer are fixed, power system stabilizer (PSS) performance is degraded whenever the operating point changes [5]. Aiming to overcome these problems, a lot of research about the power system stabilizers design has been developed, which consists of a wide range of strategies, such as adaptive sliding controllers, adaptive controllers and adaptive fuzzy controllers. Based on universal approximation theorem, many adaptive fuzzy controllers have been proposed in the literature. The common idea is to use an adaptive fuzzy system to approximate the unknown system functions. However, the robustness of the closed loop cannot be guaranteed in presence of a large disturbance.

On the other hand sliding mode control (SMC) has been widely used in the literature due to its robustness and its simplicity design. However, SMC suffers from two major shortcomings. The first one is the presence of chattering while the second consists in the fact that system dynamics must be well-known [5-6, 8].

In this paper, we propose a robust tracking control of nonlinear power system via type-2 adaptive fuzzy sliding mode method without reaching phase. This approach is a trial to combine the flexibility and intelligence of fuzzy logic with efficiency and robustness of SMC. The main contributions presented in this paper consist mainly in SMC reaching phase elimination, replacement of the switching function of SMC by a smooth and the use of type-2 fuzzy to really account for fast varying operating conditions. Furthermore the used mathematical development permits to overcome the previous disadvantages of classical sliding mode. For this, we use two type-2 adaptive fuzzy systems to approximate the unknown dynamics [7-9].

This paper introduces in the next section the model of power system, followed by the second section in which sliding mode without reaching phase and chattering technique is discussed. In third section the design of the type-2 adaptive fuzzy sliding control is presented and stability issue proved followed by simulation and a presentation of results for different operating conditions followed by a brief conclusion.

POWER SYSTEM MODEL

In this paper, a simplified dynamic model of a power system, namely, a single machine infinite bus (SMIB) power system is considered [4]. It consists of a single synchronous generator connected through a parallel transmission line to a very large network approximated by an infinite bus. The classic representation of synchronous machine infinite bus SMIB power system can be written as follows [1-4]:

Mechanical Equations

$$\dot{\delta} = \omega_0\left(\omega - \omega_{ref}\right) \tag{1}$$

$$\dot{\omega} = \frac{1}{M}\left(P_m - P_e\right) \tag{2}$$

Electrical Generator Dynamics

$$\dot{e}_q{}' = \frac{1}{T'_{d0}}\left(e_{fd} - e_q\right) \tag{3}$$

$$\dot{e}_{fd} = \frac{1}{T_A}\left(K_A\left(E_{ref} - V_t + u\right) - e_{fd}\right) \tag{4}$$

Electrical Equations

$$e_q = e'_q + \left(x_d - x'_d\right)i_d \tag{5}$$

$$e_{fd} = k_f u_f(t) \tag{6}$$

$$P_e = \frac{e'_q V}{x'_{ds}} \sin\delta(t) \tag{7}$$

More details about power system modeling and definition of the parameters can be found in [4].

Nonlinear Model of Power System

A nonlinear representation of the machine during a transient period after a major disturbance has occurred in the system can be written as follows:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x,t) + g(x,t)u \end{cases} \tag{8}$$

where $x = \left[\Delta\omega \quad \Delta P/M\right]^T \in R^2$ is the state vector in which $\Delta\omega$ is speed deviation, $\Delta P = P_m - P_e$ is the accelerating power, M is inertia moment coefficient, $u \in R$ is the input, $f(x,t)$ and $g(x,t)$ are two nonlinear unknown functions to be approximated by fuzzy systems , such that:

$$\Delta\dot{P} = -\dot{P}_e \tag{9}$$

Post fault the mechanical input power is considered constant during the transient regime that is for first few seconds after the disturbance has occurred [6-8].

SLIDING MODE CONTROL WITHOUT REACHING PHASE AND CHATTERING

Sliding mode control techniques are well known for their invariant properties to certain parameter variations and external disturbances and have been successfully applied in many fields. Sliding mode control approach involves two phases, reaching phase and sliding phase. During the first phase, the system is sensitive to uncertainties and disturbances thus its elimination should result in considerable amelioration of system robustness.

Consider a single-input single-output nonlinear system described in (8). In order to avoid the problems of the reaching phases and the chattering, let the sliding surface be chosen as:

$$S = x_2 + \beta x_1 - e^{-t}\left(x_2(0) + \beta x_1(0)\right) \tag{10}$$

where β is a positive constant, $x_1(0)$ and $x_2(0)$ represent the initial states.
Time derivative if the sliding surface is given by:

$$\dot{S} = \dot{x}_2 + \beta x_2 + e^{-t}\left(x_2(0) + \beta x_1(0)\right) \tag{11}$$

Using (11), to satisfy the attracting condition (12), we propose the following theorem:

$$S\dot{S} < 0 \tag{12}$$

Theorem 1: For the nonlinear system (8), if we choose the following control law without reaching phase and chattering:

$$u = -g^{-1}(x)\left(f(x) + \beta x_2 + e^{-t}\left(x_2(0) + \beta x_1(0)\right) + \frac{S}{\rho^2} \right) \tag{13}$$

where ρ is a positive constant, then the system is stable.

Proof
Choosing the Lyapunov function candidate to be

$$V = \frac{1}{2} S^T S \ , \tag{14}$$

Therefore

$$\dot{V} = S^T \dot{S} \tag{15}$$

$$= S\left[\dot{x}_2 + \beta x_2 + e^{-t}\left(x_2(0) + \beta x_1(0)\right)\right] \tag{16}$$

$$= S\left[f(x) + g(x)u + \beta x_2 + e^{-t}\left(x_2(0) + \beta x_1(0)\right)\right] \tag{17}$$

$$= -\left(\frac{S}{\rho}\right)^2 \tag{18}$$

thus: $\dot{V} \le 0$. (19)

The control low (13) allows ensuring the system stabilization and robustness but cannot be directly implemented due to unknown function $f(x,t)$ and $g(x,t)$. In the next section, we propose a new control law to overcome this problem.

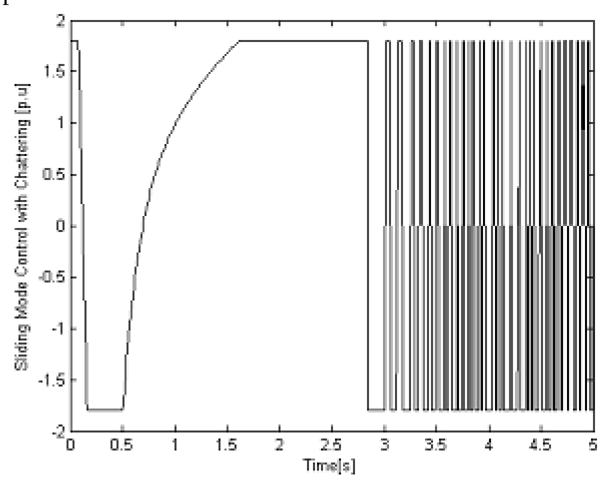


Fig.1 (a) Sliding mode control with chattering

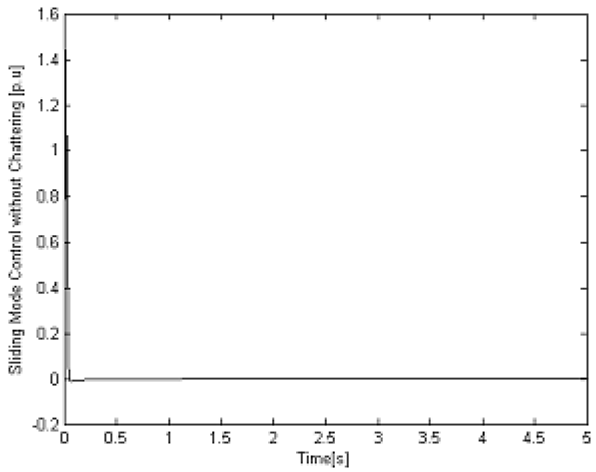


Fig. 1 (b) Sliding mode control without chattering

TYPE-2 ADAPTIVE FUZZY SLIDING MODE CONTROL

Power system operating point varies constantly and $f(x,t)$ and $g(x,t)$ cannot be known accurately at all time except through and adaptive scheme and some mean of estimating system nonlinear dynamics. We propose to use two type-2 adaptive fuzzy systems to approximate $f(x,t)$ and $g(x,t)$. A fuzzy system that uses type-2 fuzzy sets and/or fuzzy logic and inference is called a type-2 fuzzy system. In contrast, a fuzzy system that employs ordinary fuzzy sets, logic, and inference is called type-1 fuzzy system [7].

Type-1 fuzzy systems, especially fuzzy controllers and fuzzy models, have been developed and applied to practical problems. A type-1 fuzzy set has a grade of membership that is crisp, whereas a type-2 fuzzy set (T2FS) has a membership grade that is fuzzy, so T2FS are 'fuzzy–fuzzy' sets and can better account for uncertainties. One way of representing the fuzzy membership of fuzzy sets is to use the footprint of uncertainty (FOU), which is a 2-D representation, with uncertainties about the left and pairs of the left side of the membership function and also about the right and pair of the right side of the membership function.

Operation of type-2 interval fuzzy set is identical with the operation of type-1 fuzzy set. However type-2 fuzzy system is an interval fuzzy system where fuzzy operation is done with two type-1 membership functions, upper membership function (UMF) and lower membership function (LMF), to produce the firing strength as shown in Fig.2 this UMF and LMF will delimit the foot of uncertainty. Defuzzification is a mapping process from fuzzy logic control action to a non-fuzzy (crisp) control action.

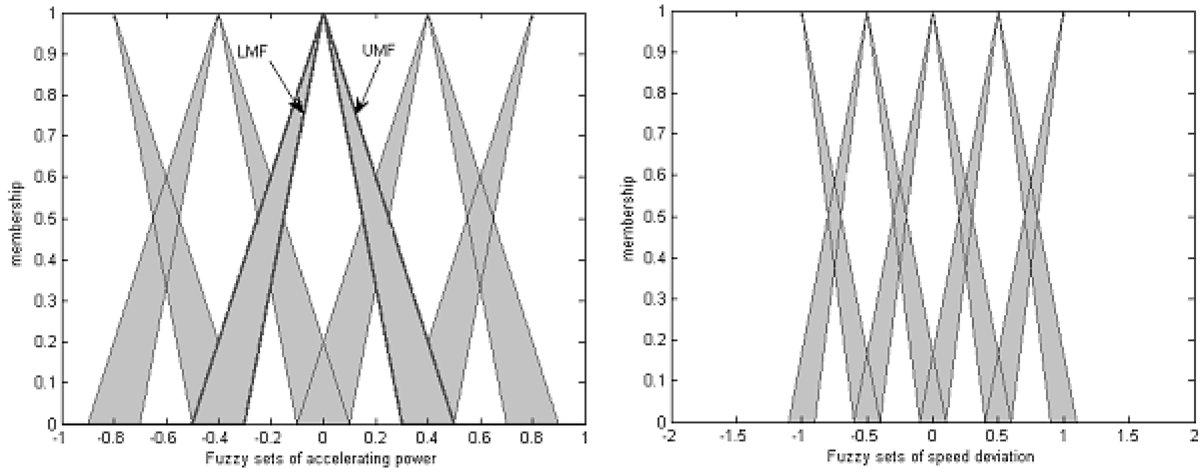


Fig. 2 (a) Type-2 fuzzy sets for input ΔP **Fig. 2 (b) Type-2 fuzzy sets for input** $\Delta\omega$

A type-2 fuzzy set consists of two separate membership functions, primary and secondary membership function. At each value of primary variable the membership is a function and it is not just a crisp value; here, both primary and secondary membership functions will be in the interval [0, 1]. Since, the FOU is not a single point but designed over an interval, type-2 fuzzy logic controller can also be referred as interval type-2 fuzzy logic controller.

This effect of taking their FOU over a range or an interval gives the 3-dimensional effect. The architecture of a type-2 fuzzy logic controlled system is shown in Fig. 3 which contains the following five components: fuzzifier, rule base, fuzzy inference engine, type-reducer, and defuzzifier.

The type-2 fuzzy logic systems have been employed in modelling and controlling nonlinear systems due to their inherent capabilities of nonlinear function approximation.

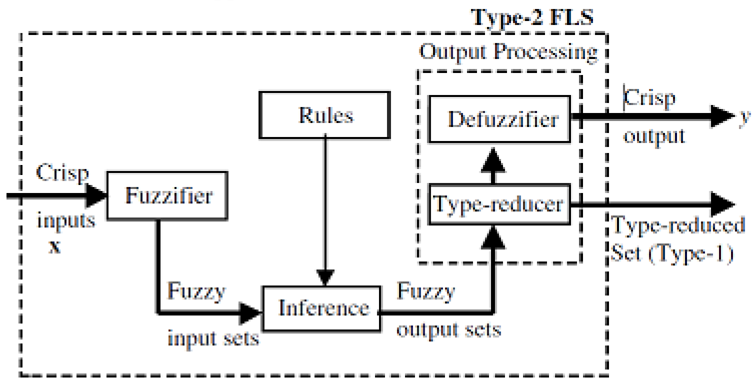


Fig.3 Type-2 fuzzy logic system

Based on the universal approximation theorem, unknown functions $f(x,t)$ and $g(x,t)$ can be approximated by:

$$\hat{f}(x,\theta_f) = \xi^T(x)\theta_f \tag{20}$$

$$\hat{g}(x,\theta_g) = \xi^T(x)\theta_g \tag{21}$$

where $\theta = [\theta_1, \theta_2, ..., \theta_m]$ is the vector of parameters, $\xi = [\xi_1, \xi_2, ..., \xi_m]^T$ is the vector of fuzzy basis functions (FBF), such that:

$$\xi^T\theta_f = \frac{1}{2}[\xi_r^T \xi_l^T][\theta_{fr}\theta_{fl}] \tag{22}$$

$$\xi^T\theta_g = \frac{1}{2}[\xi_r^T \xi_l^T][\theta_{gr}\theta_{gl}] \tag{23}$$

where: $\xi_l = \left[\xi_l^1, \xi_l^2, \ldots, \xi_l^m\right]^T$, $\xi_r = \left[\xi_r^1, \xi_r^2, \ldots, \xi_r^m\right]^T$, $\theta_r = \left[\theta_{1r}, \theta_{2r}, \ldots, \theta_{mr}\right]$ and $\theta_l = \left[\theta_{1l}, \theta_{2l}, \ldots, \theta_{ml}\right]$.
This yields a minimum approximation error:

$$\varepsilon = \delta_f + \delta_g u \tag{24}$$

where:

$$\delta_f = f(x) - \xi^T(x)\theta_f^* \tag{25}$$

$$\delta_g = g(x) - \xi^T(x)\theta_g^* \tag{26}$$

and θ_f^*, θ_g^* are the optimal approximation parameters and letting:

$$\tilde{\theta}_f = \theta_f - \theta_f^* \tag{27}$$

$$\tilde{\theta}_g = \theta_g - \theta_g^* \tag{28}$$

Theorem 2: For the nonlinear system (8), if we choose the following control law:

$$u = -\hat{g}^{-1}(x)\left(\hat{f}(x) + \beta x_2 + e^{-t}\left(x_2(0) + \beta x_1(0)\right) + \frac{S}{\rho^2}\right) \tag{29}$$

and the adaptation laws:

$$\dot{\theta}_f = \gamma_1 S \xi(x) - \gamma_1 \theta_f \tag{30}$$

$$\dot{\theta}_g = \gamma_2 S \xi(x) - \gamma_2 \theta_g \tag{31}$$

then the stability of the closed loop system is guaranteed.

Proof
Choosing the Lyapunov function candidate to be

$$V = \frac{1}{2}S^T S + \frac{1}{2\gamma_1}\tilde{\theta}_f^T\tilde{\theta}_f + \frac{1}{2\gamma_2}\tilde{\theta}_g^T\tilde{\theta}_g\,, \tag{32}$$

Therefore

$$\dot{V} = S^T\dot{S} + \frac{1}{\gamma_1}\tilde{\theta}_f^T\dot{\theta}_f + \frac{1}{\gamma_2}\tilde{\theta}_g^T\dot{\theta}_g \tag{33}$$

$$= S^T\left(\dot{x}_2 - \hat{g}(x,\theta_g)u - \hat{f}(x,\theta_f) - \frac{S}{\rho^2}\right) + \frac{1}{\gamma_1}\tilde{\theta}_f^T\dot{\theta}_f + \frac{1}{\gamma_2}\tilde{\theta}_g^T\dot{\theta}_g \tag{34}$$

$$= S^T\left(-\left(\hat{f}(x,\theta_f) - f(x)\right) - \left(\hat{g}(x,\theta_g) - g(x)\right)u - \frac{S}{\rho^2}\right) + \frac{1}{\gamma_1}\tilde{\theta}_f^T\dot{\theta}_f + \frac{1}{\gamma_2}\tilde{\theta}_g^T\dot{\theta}_g \tag{35}$$

$$= S^T\left(-\tilde{\theta}_f^T\xi(x) - \tilde{\theta}_g^T\xi(x)u + \varepsilon - \frac{S}{\rho^2}\right) + \frac{1}{\gamma_1}\tilde{\theta}_f^T\dot{\theta}_f + \frac{1}{\gamma_2}\tilde{\theta}_g^T\dot{\theta}_g \tag{36}$$

Using (30) and (31), we can obtain

$$\dot{V} = -\frac{S}{\rho^2} - \tilde{\theta}_f^T\dot{\theta}_f - \tilde{\theta}_g^T\dot{\theta}_g + \varepsilon S \tag{37}$$

Since the following inequalities are valid

$$-\tilde{\theta}_f^T\theta_f \le -\frac{1}{2}\tilde{\theta}_f^T\tilde{\theta}_f + \frac{1}{2}\left\|\theta_f^*\right\|^2 \tag{38}$$

$$-\tilde{\theta}_g^T\theta_g \le -\frac{1}{2}\tilde{\theta}_g^T\tilde{\theta}_g + \frac{1}{2}\left\|\theta_g^*\right\|^2 \tag{39}$$

we can rewrite $\dot{V}$ as follows

$$\dot{V} \le -\left(\frac{S}{\rho^2} + \frac{1}{2}\tilde{\theta}_f^T\tilde{\theta}_f + \frac{1}{2}\tilde{\theta}_g^T\tilde{\theta}_g\right) + \left\|\varepsilon S\right\| + \frac{1}{2}\left\|\theta_f^*\right\|^2 + \frac{1}{2}\left\|\theta_g^*\right\|^2 \tag{40}$$

Let $\alpha = \min\left(\frac{2}{\rho^2}, \gamma_1, \gamma_2\right)$ and $\mu = \frac{1}{2}\left\|\theta_f^*\right\|^2 + \frac{1}{2}\left\|\theta_g^*\right\|^2 + \left\|\varepsilon S\right\|$ then: $\dot{V} \le -\alpha V + \mu$
(41)
Multiplying both sides by $e^{\alpha t}$, we can have the following inequality

$$\frac{d}{dt}\left(Ve^{\alpha t}\right) \le \mu e^{\alpha t} \tag{42}$$

Integrating this last equation from 0 to t, we have

$$0 \le V(t) \le \left(V(0) - \frac{\mu}{\alpha}\right)e^{-\alpha t} + \frac{\mu}{\alpha} \tag{43}$$

$$0 \le V(t) \le V(0) + \frac{\mu}{\alpha} \tag{44}$$

$$0 \le V(t) \le \eta . \tag{45}$$

where: $$\eta = V(0) + \frac{\mu}{\alpha} . \tag{46}$$

Using the Barbalat lemma, we can conclude that S and $\dot{S}$ are bounded ($S \in L_\infty$ and $\dot{S} \in L_\infty$). Since ε, $\tilde{\theta}_f$ and $\tilde{\theta}_g$ are bounded, we can conclude directly that $V(t)$ is also bounded which guarantees closed loop stability.

SIMULATION

To show the performances and the robustness of the proposed approach comparative study with a classic CPSS is presented. Five type-2 fuzzy sets for each input are sufficient for our PSS design. The fuzzy sets for inputs $\Delta\omega$ and ΔP are defined according to the membership functions shown in fig. 2 (a) and fig. 2 (b).

Simulation Cases of Single-Machine Infinite Bus System

First the simulation results for normal load conditions are shown in fig.4 (a) and fig.4 (b) with PSS based on proposed control. Performances of the proposed PSS are clearly superior while a greater control effort is solicited. To further test our proposed PSS let operating conditions be changed abruptly from light to heavy load condition, i.e. Q is changed from 0.3 p.u. to 0.8 *p.u* and $x_e = 0.45\,p.u.$ The simulation results given in fig. 5(a) and fig.5 (b) show a better transient performance. We now consider the case of the sudden occurrence of reactive power import causing a change in Q to *-0.3 p.u* and strong connection ($x_e = 0.1$ *p.u*). Again the simulation results shown in fig.6 (a) and fig.6(b) seem to indicate a good transient behaviour showing superior performance of the proposed PSS.

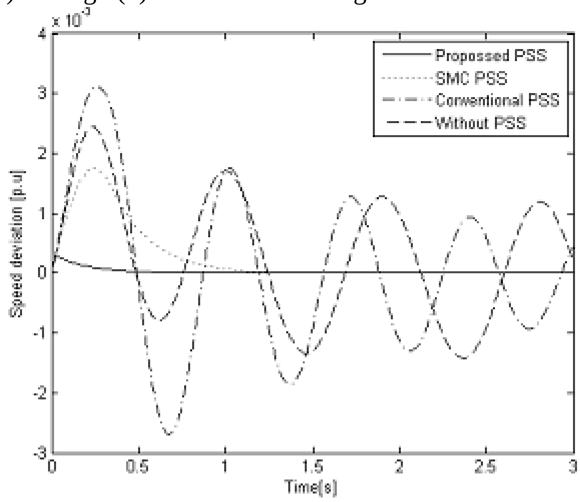


Fig. 4 (a) Speed deviation

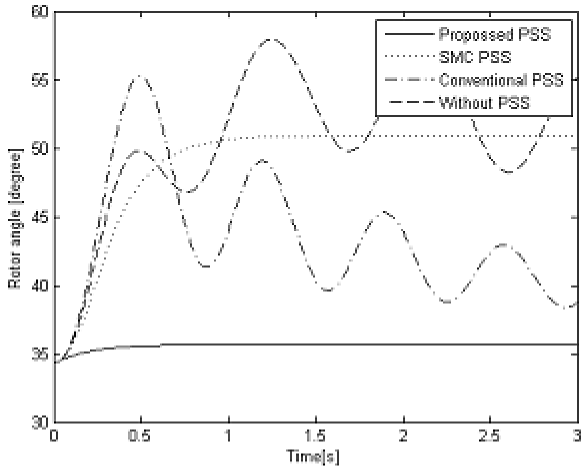


Fig.4 (b) Rotor angle

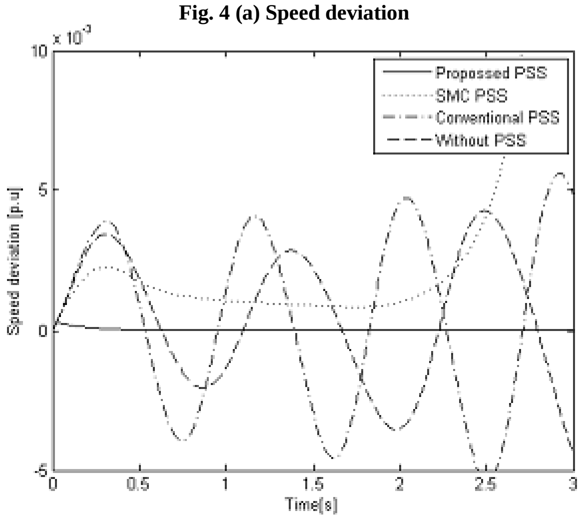


Fig.5(a) Speed deviation in heavy reactive power case

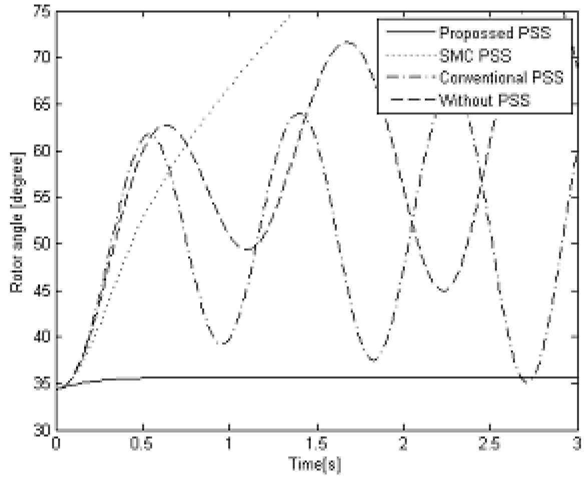


Fig.5 (b) Rotor angle in heavy reactive power case

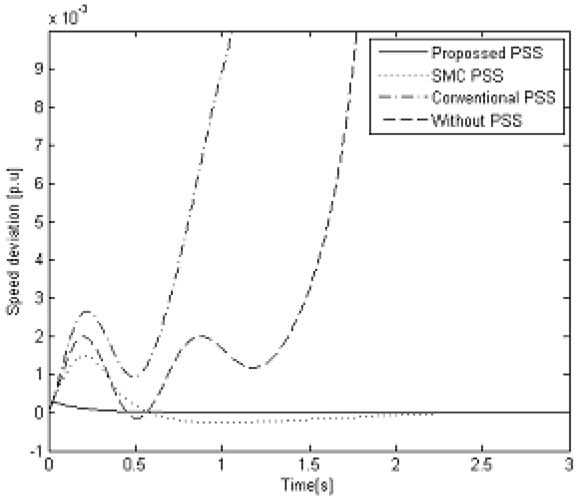


Fig.6 (a) Speed deviation for strong connection

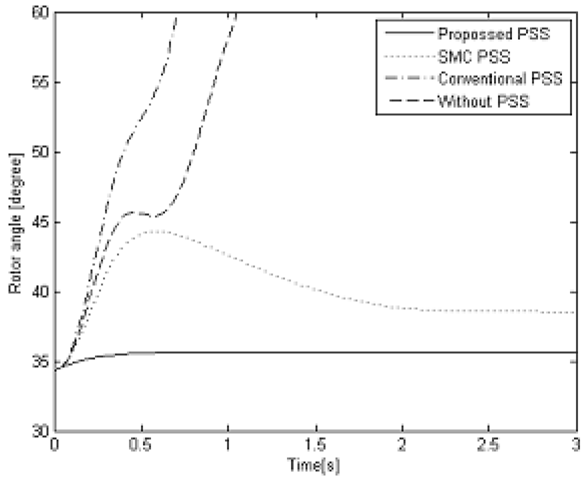


Fig.6 (b) Rotor angle for strong connection

Simulation Cases of Multi-Machine Power System

To demonstrate the performance of the proposed control, we performed nonlinear simulation for multi-machine system as in fig.7. We compared the proposed T2AFS PSS with the conventional power system stabilizer CPSS. As shown fig.8 (a) and fig.8 (b), the proposed approach shows better control performance than conventional PSS in terms of settling time and damping effect. To further evaluate the robustness of proposed control, fig.9 (a) and fig.9 (b) show good performance while the power system is subjected to heavy loading.

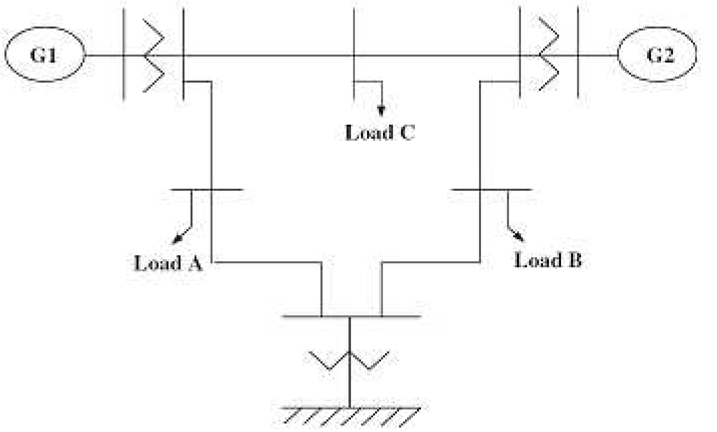


Fig.7 Multi machine power system

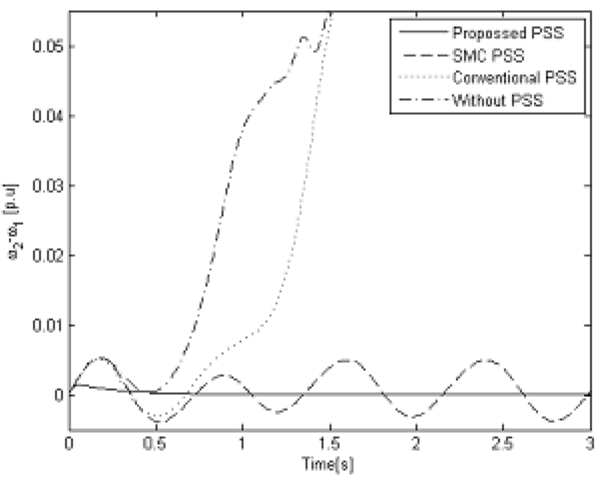


Fig.8 (a) Response of multi-machine power system: speed deviation

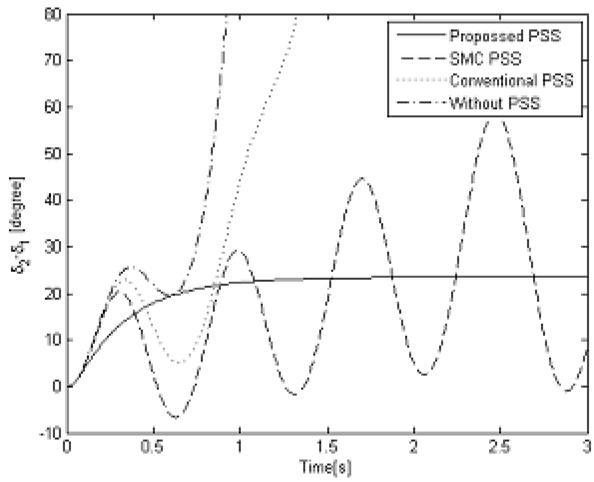
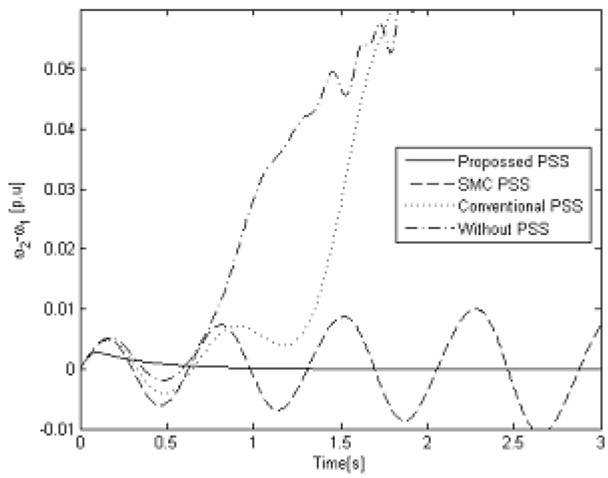


Fig.8 (b) Response of multi-machine power system: rotor angle

(Under nominal load)



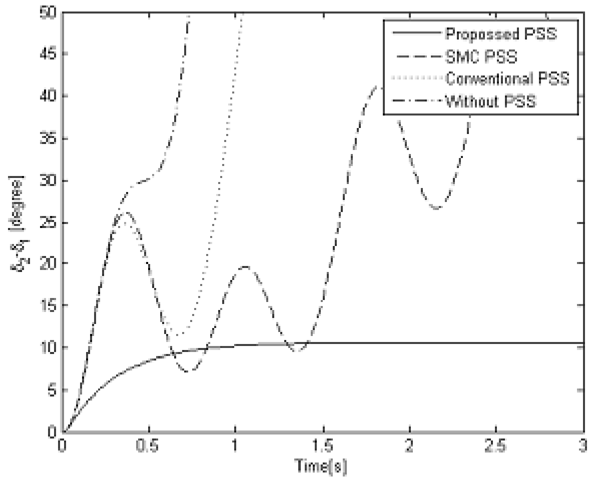


Fig.9(a) Response of multi-machine power system: speed deviation **Fig.9 (b) Response of multi-machine power system: rotor angle. (Under heavy load)**

CONCLUSION

This paper presents a novel approach for the design of type-2 adaptive fuzzy sliding mode power system stabilizer for a multi-machine power system. Simulation results reveal that the performance of a sliding mode control without reaching phase and chattering based adaptive type-2 fuzzy power system stabilizer in a multi-machine power system is quite robust under wide variations of loading conditions both for small and large disturbance. The coordination between sliding power system stabilizer (SPSS) and type-2 adaptive fuzzy system (AT2F) has been presented for two machines. Simulation results for small perturbation and large fault at different loading conditions demonstrated the effectiveness of the proposed approach.

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