1. Imene DEHIBA[1], 2. Mohamed ABID[1], 3. Abdelghani AISSAOUI[1], 4. Boubeker DEHIBA[1]

IRECOM Laboratory, Department of Electrical Engineering, Djillali Liabes University of Sidi Bel Abbes,22000, Algeria (1),
ORCID. 1. 0000-0002-3799-6476, 2. 0000-0002-2070-801X, 3. 0000-0001-6211-5063, 4. /0000-0002-0175-0140

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Robust control of power system stabilizer using sliding mode approach

Abstract*. This paper proposes a method of sliding mode control (SMC) approach for excitation control in a single generator-infinite bus power system. Conventional power system stabilizer (C-PSS) design becomes a complicated problem in presence of internal and external disturbances to the excitation of a power system. Improving the stability of the power system has become a priority objective. The aim of this work is to ensure maximum damping of the electromechanical oscillations of the Single Machine Infinity Bus System (SMIB) by the power stabilizers based on the sliding mode control technique. The effectiveness of the proposed approach is demonstrated through computer simulations on two different cases of operating conditions. The performance of the proposed approach is evaluated in terms of damping power system oscillations. The obtained results show the high performance of the proposed controller to improve the stability of the power system compared to the C-PSS and found to be impressive.*

Streszczenie. *W artykule zaproponowano metodę sterowania trybem ślizgowym (SMC) do sterowania wzbudzeniem w pojedynczym generatorowo-nieskończonym systemie zasilania szyny. Konstrukcja konwencjonalnego stabilizatora systemu elektroenergetycznego (C-PSS) staje się skomplikowanym problemem w obecności wewnętrznych i zewnętrznych zakłóceń wzbudzenia systemu elektroenergetycznego. Poprawa stabilności systemu elektroenergetycznego stała się celem priorytetowym. Celem pracy jest zapewnienie maksymalnego tłumienia oscylacji elektromechanicznych systemu SMIB (Single Machine Infinity Bus System) przez stabilizatory mocy oparte na technice sterowania ślizgowego. Skuteczność proponowanego podejścia demonstrowana jest poprzez symulacje komputerowe w dwóch różnych przypadkach warunków pracy. Skuteczność proponowanego podejścia oceniana jest pod kątem tłumienia oscylacji systemu elektroenergetycznego. Uzyskane wyniki wskazują na wysoką wydajność proponowanego sterownika w celu poprawy stabilności systemu elektroenergetycznego w porównaniu z C-PSS i okazały się imponujące.* (***Odporne sterowanie stabilizatora systemu zasilania przy użyciu trybu ślizgowego***)

Keywords: Single Machine Infinite Bus (SMIB), Sliding Mode Control (SMC), Power system Stabilizer (PSS).
Słowa kluczowe:.
Stabilizaja systemu energetycznego, sterowanie ślizgowe

Introduction

In the power system, an important condition on the stable operation of power system is reliability and continuity of the power supply. In this case, more and more scholars have paid attention to the stability control of generators. Among them, the excitation control of generator is an economic and effective way to improve stability. The Automatic Voltage Regulator (AVR) and the power system stabilizer (PSS) can play a major role in a power system's stability. Essentially, the AVR and PSS trade off against one other. The high gain fast response of the AVR decreases power system oscillation stability and increases transient stability, and vice versa. In contrast, the PSS reduces the transient stability by overriding the voltage signal to the exciter and growing the oscillation stability [1-16].

The design of the PSS is mainly based on a linearized power system model obtained at a specific operating point. However, in practice the operating point of a power system can shift due to several factors, such as short circuits and changes in the network topology, thereby producing stability problems which may not be satisfactorily overcome by PSS controllers [6].

Therefore, to solve these problems, the attention of researchers has focused on the design of controllers based on artificial intelligence techniques such as fuzzy logic [17], adaptive fuzzy [18], neural networks [19], neuro-fuzzy [20].

In this article, we propose a method for designing an intelligent stabilizer based on the sliding mode theory, applied to a single generator-infinite bus power system. This type of control has many advantages such as good robustness, high accuracy, good stability and fast response time. This makes it particularly suitable for handling systems with uncertainties. The uncertainty effect can be due to the parameter variations of the system, surrounding disturbances, fault in the measurement sensors or actuators and the simplifications on the system model.

The results obtained for two types of disturbances: a three-phase short-circuit fault and a sudden 10% increase in mechanical input power, the stabilizer performance per sliding mode was compared with the conventional stabilizer.

Power system model of SMIB

The studied system consists of the single machine connected to an infinite bus through a transmission line. Synchronous generator control components are shown in Figure 1.

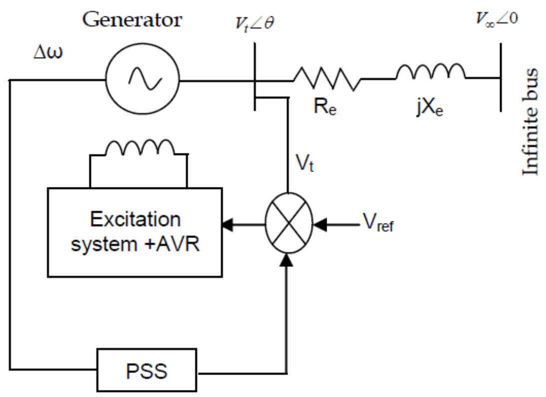

Fig. 1. SMIB system the excitation of the Generator.

(1) $$\frac{d\delta}{dt} = \omega - \omega_s$$

(2) $$\frac{d\omega}{dt} = \frac{\omega_s}{2H}\left(T_m - T_e - D\left(\omega - \omega_s\right)\right)$$

(3) $$\frac{de_q^{'}}{dt} = -\frac{1}{T_{d0}^{'}}\left(e_q^{'} + \left(x_d - x_d^{'}\right)i_d - e_{fd}\right)$$

(4) $$\frac{de_{fd}}{dt} = -\frac{1}{T_a}e_{fd} + \frac{K_a}{T_a}\left(v_{ref} - v_t\right)$$

(5) $T_e = e_q^{'} i_q + \left(x_q - x_d^{'} \right) i_d i_q$

(6) $x_q i_q - v_d = 0$

(7) $e_q^{'} - v_q - x_d^{'} i_d = 0$

(8) $r_e i_d - x_e i_q = v_d - v_\infty \sin(\delta)$

(9) $x_e i_d + r_e i_q = v_q - v_\infty \cos(\delta)$

(10) $v_t^2 = v_d^2 + v_q^2$

(1) - (4) are the differential equations of the power system.
(6) - (7) are algebraic stator equations.
(8) - (10) are the network equations.

where: δ –Rotor angle; ω – Rotor speed; ω_s – Synchronous speed; T_m Mechanical torque input; T_e – Electromagnetic torque; D – Damping coefficient ; H – Inertia constant ; e_{fd} – Excitation voltage ; e'_q – q-axis transient voltage ; T_{d0} – d-axis transient time constant; x_d – d-axis synchronous reactance; x_q – q-axis synchronous reactance; x'_d – d-axis transient reactance; v_t – Generator terminal voltage ; v_{ref} – Reference voltage; K_a – Gain of excitation voltage; T_a – Time constants of excitation voltage.

Power system stabilizer (PSS)

The studied system is equipped with AVR and C-PSS. The C-PSS is shown in Fig. 2. The AVR is used in the excitation system to keep the terminal voltage at the desired level.

In this work, a first order model of voltage regulator is used eq.4. The AVR parameters to adjust are the Ka and Ta.

The PSS is used to attenuate oscillating signals with low frequency especially the rotor oscillations of generator. Rotor oscillations are produced mainly by rotor speed deviations. The PSS generate supplementary control signals for the excitation system in order to damp the low frequency power system oscillations. Additional damping is primarily required under conditions of heavy load and line outages. Hence, systems which normally have adequate damping can often benefit from stabilizers during such abnormal conditions.

The input of this PSS is the generator speed deviation. The PSS model contains the gain block and a phase compensating block. The PSS output is transmitted to the excitation of the generator.

The structure of PSS is mainly composed by a gain, wash out filter and the phase compensator block. The gain block determines the damping ratio of PSS and its value is determined by practical considerations. The washout filter behaves as a high pass filter therefore the PSS only responds to the speed deviation of generator and not responds to the steady state operation of system. The lag compensation between excitation input and electrical torque (air–gap torque) is provided by the phase compensator block. The limiting block at the output of PSS is connected to prevent the over excitation. The bounds of limiting block are taken as ±0.02 to ±0.05 pu [21].

The PSS is represented by Fig.2, and characterized by the following transfer function equation:

(11) $H(s) = K_{PSS} \left(\dfrac{sT_W}{1+sT_W} \right) \left(\dfrac{1+sT_1}{1+sT_2} \right)$

where: T_W is the wash out time constant. T_1-T_2 are PSS time constants and K_{PSS} is the PSS gain. Typical values of the parameters are [1]:

K_{PSS} is in the range of 0.1 to 50; T_1 is the lead time constant, 0.2 to 1.5 sec; T_2 is the lag time constant, 0.02 to 0.15 sec.

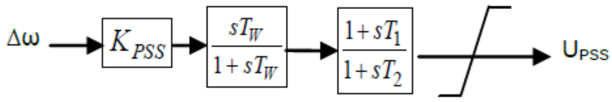

Fig. 2. –Block diagram of the PSS

This design of conventional PSS is based on a linearized model around a certain operating point. Since the actual power system operates over a wide range of operating conditions and nonlinear characteristics. The tuning of C-PSS to cope with most of the operating conditions is very difficult.

In this work we will use a nonlinear type control with variable structure in order to overcome these difficulties.

Sliding mode control

The sliding mode control knows a big success these last years. It is due to the implementation simplicity and the robustness with regard to the system uncertainties and the external disturbances. The SMC consists to return the state trajectory towards the sliding surface and to develop it above, with a certain dynamic up to the equilibrium [10–11]. Its design consists mainly to determine three stages.

1. The switching surface choice

For a non-linear system represented by the following equation:

(12) $\dot{x} = f(X,t) + g(X,t) \quad u(X,t); \quad X \in R^n, \quad u \in R$

Where: $f(X,t)$, $g(X,t)$ are two continuous and uncertin non-linear function , supposed limited.

We take the general equation to determine the sliding surface , proposed by J.J. Slotine, given by:

(13) $S(X) = \left(\dfrac{d}{dt} + \lambda \right)^{n-1} e$

(14) $e = X^d - X; \quad X = \left[x, \dot{x}, \quad \ldots, x^{n-1} \right]^T;$
$X^d = \left[x^d, \dot{x}^d, \ddot{x}^d, \ldots \right]^T$

where: e – error on the signal to be adjusted, λ – positive coefficient, n – system order, X^d – desired signal, X – state variable of the control signal.

2. Convergence condition

The convergence condition is defined by the Lyapunov equation, it makes the surface attractive and invariant

(15) $S(X)\dot{S}(X) \le 0$

3. Control calculation

The control algorithm is defined by the relation

(16) $u_{PSS} = u_{eq} + u_n$

Where: u_{PSS} – control signal, u_{eq} – equivalent control signal, u_n – switching control term, sat $(S(X)/\varphi)$ – saturation function, φ – threshold width of the saturation function.

(17) $u_n = u_{\max} sat\left(S(X)/\varphi \right)$

(18) $sat\left(S(X)/\varphi \right) = \begin{cases} sgn(S) & if \quad |S| \rangle \varphi \\ S/\varphi & if \quad |S| \langle \varphi \end{cases}$

The proposed control

To control Δω the deviation of the angular speed, we introduce the variables of the derivative of angular speed and the acceleration of angular speed. The tracing error is $e = \Delta\omega^d - \Delta\omega$.

We set n=2, the proposed sliding surface and its derivative are:

$$S(e) = \Delta\dot{\omega}^d - \Delta\dot{\omega} + \lambda(e) \quad (19)$$

$$\dot{S}(\Delta\omega) = \Delta\ddot{\omega}^d - \Delta\ddot{\omega} - \Delta\dot{\omega} + \lambda(\dot{e}) \quad (20)$$

Replacing the derivative of expression (2) in equation (20), we get:

$$\dot{S}(\Delta\omega) = \Delta\ddot{\omega}^d - \Delta\dot{\omega} + \lambda(\dot{e}) - \frac{1}{2H}\frac{d}{dt}\left(T_m - T_e - D(\omega - \omega_s)\right) \quad (21)$$

$$\dot{S}(\Delta\omega) = \Delta\ddot{\omega}^d - \Delta\dot{\omega} + \lambda(\dot{e}) - \frac{1}{2H}\frac{d}{dt}(-T_e) \quad (22)$$

We replacing the expression derivative of T_e in the expression (22), we obtain :

$$\begin{aligned}\dot{S}(\Delta\omega) &= \Delta\ddot{\omega}^d - \Delta\dot{\omega} + \lambda(\dot{e}) \\ &+ \left(\frac{1}{2H}\right)\left(i_q \frac{d}{dt}e_q^{'} + e_q^{'}\frac{d}{dt}i_q\right) \\ &+ \left(\frac{1}{2H}\right)\left(\left(x_q - x_d^{'}\right)i_q \frac{d}{dt}i_d\right) \\ &+ \left(\frac{1}{2H}\right)\left(\left(x_q - x_d^{'}\right)i_d \frac{d}{dt}i_q\right)\end{aligned} \quad (23)$$

We replacing the expression of $\frac{d}{dt}e_q^{'}$ by its eq (3) in the expression (23), we obtain :

$$\begin{aligned}\dot{S}(\Delta\omega) &= \Delta\ddot{\omega}^d - \Delta\dot{\omega} + \lambda(\dot{e}) \\ &+ \left(\frac{1}{2H}\right)\left(\left(-\frac{1}{T_{d0}^{'}}\right)\left(e_q^{'} + \left(x_d - x_d^{'}\right)i_d - e_{fd}\right)i_q\right) \\ &+ \left(\frac{1}{2H}\right)\left(\frac{d}{dt}i_q e_q^{'} + \left(x_q - x_d^{'}\right)\left(i_q \frac{d}{dt}i_d + i_d \frac{d}{dt}i_q\right)\right)\end{aligned} \quad (24)$$

We replacing the expression of e_{fd} by its eq (4) in the expression (24), we obtain:

$$\begin{aligned}\dot{S}(\Delta\omega) &= \Delta\ddot{\omega}^d - \Delta\dot{\omega} + \lambda(\dot{e}) \\ &- \left(\frac{i_q}{2H.T_{d0}^{'}}\right)\left(e_q^{'} + \left(x_d - x_d^{'}\right)i_d\right) \\ &- \left(\frac{i_q}{2H.T_{d0}^{'}}\right)\left(T_a \frac{d}{dt}e_{fd} - K_a\left(v_{ref} - v_t\right) - K_a u_{PSS}\right) \\ &+ \left(\frac{1}{2H}\right)\left(\frac{d}{dt}i_q e_q^{'} + \left(x_q - x_d^{'}\right)\left(i_q \frac{d}{dt}i_d + i_d \frac{d}{dt}i_q\right)\right)\end{aligned} \quad (25)$$

with reorganization of the expression obtained, we deduce the following expression

$$\begin{aligned}\dot{S}(\Delta\omega) &= \Delta\ddot{\omega}^d - \Delta\dot{\omega} + \lambda(\dot{e}) \\ &- \left(\frac{i_q}{2H.T_{d0}^{'}}\right)\left(e_q^{'} + \left(x_d - x_d^{'}\right)i_d\right) \\ &- \left(\frac{i_q}{2H.T_{d0}^{'}}\right)\left(T_a \frac{d}{dt}e_{fd} - K_a\left(v_{ref} - v_t\right)\right) \\ &+ \left(\frac{1}{2H}\right)\left(\frac{d}{dt}i_q e_q^{'} + \left(x_q - x_d^{'}\right)\left(i_q \frac{d}{dt}i_d + i_d \frac{d}{dt}i_q\right)\right) \\ &+ \frac{K_a i_q}{2H.T_{d0}^{'}}u_{PSS}\end{aligned} \quad (26)$$

The expression (26) can be written

$$\dot{S}(\Delta\omega) = \Delta\ddot{\omega}^d - \Delta\dot{\omega} + \lambda(\dot{e}) - f(x,t) - B(x)u_{PSS}(t) \quad (27)$$

Where:

$$\begin{aligned}f(x,t) &= \frac{i_q}{2H.T_{d0}^{'}}\left(e_q^{'} + \left(x_d - x_d^{'}\right)i_d\right) \\ &+ \frac{i_q}{2H.T_{d0}^{'}}\left(T_a \frac{d}{dt}e_{fd} - K_a\left(v_{ref} - v_t\right)\right) \\ &- \left(\frac{1}{2H}\right)\left(\frac{d}{dt}i_q e_q^{'} + \left(x_q - x_d^{'}\right)\left(i_q \frac{d}{dt}i_d + i_d \frac{d}{dt}i_q\right)\right)\end{aligned} \quad (28)$$

$$B(x) = \frac{-K_a i_q}{2H.T_{d0}^{'}} \quad (29)$$

Replacing u by $u_{eq}+u_n$, the control appears clearly in the following equation:

During the sliding mode and in steady state, we have:

$$S(e) = 0, \quad \dot{S}(e) = 0, \quad u_{eq} = 0 \quad (30)$$

The equivalent control amount u_{eq}, is found from the previous equations and written as:

$$u_{eq} = \left(\frac{2H.T_{d0}^{'}}{K_a}\right)\left(\Delta\ddot{\omega}^d - \Delta\dot{\omega} + \lambda(\dot{e}) - f(x,t)\right) \quad (31)$$

In order to satisfy reaching conditions of sliding mode control $\dot{S}(e)S(e) \le K\left|S(e)\right|$, we must choose switching control whose control law is

$$u_n = -\left(\frac{2H.T_{d0}^{'}}{K_a}\right)K.sgn\left(S(e)\right) \quad (32)$$

To verify the system stability condition, the parameter K must be positive.

To reduce any possible overshoot of the reference voltage u_{pss}, it is often useful to add a voltage limiter.

Results and discussion

In order to verify the validity and effectiveness of the sliding mode method proposed, two types of dysfunctions are considered.

1- Large Fault Type: Three-phase short-circuit fault on sliding mode method proposed.

2- Small Fault Type: A sudden increase of 10% in mechanical power input at t = 1 s (ΔP_m = 0.10 pu).

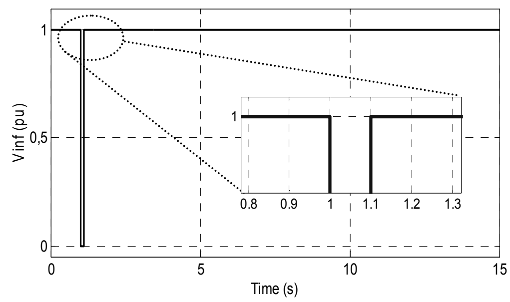

Fig. 3. The evolution of V∞.

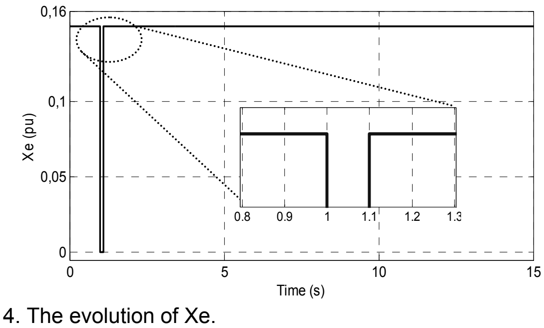

Fig. 4. The evolution of Xe.

The parameter values of considered system is shown in table 1.

Table 1. The parameter values of system

components	Parameter values
Generator	H = 3.5; T_{d0} = 5; r_s = 0.005; x_q = 0.78; x_d =1.18; x'_d = 0.2951 ; D = 0; f = 60; ω_s = 2*π*f ; e_{fd_max} = 7 ; e_{fd_min} = 0.
Transmission line	x_e = 0.15; r_e = 0; v_t = 1.05; θ^0 = 0.0715; v_∞ = 1.
The AVR	K_a = 200 ; T_a = 0.01.
PSS	K_{PSS} =0.5 ; T_W =10 ;T_1 =0.2 ;T_2 =0.1

The nominal operating point of the generator is considered at P_o = 0.8 and Q_o = 0.6.

The SM-PSS controller is designed for this type of fault since the three-phase fault has a very serious effect on the system behavior.

The time domain simulation results are presented in the following Figures:

Responses corresponding to disturbances are followed:

- For large Fault Condition: A three-phase fault was applied to the generator terminal bus at t = 1 s and it was assumed that the fault was cleared after 6 periods (range = 0.1 s).
- The system was returned to its old operating conditions by correcting the fault.
- In the case of this three-phase fault, the speed deviation ($\Delta\omega$), the rotor angle (δ) and the electromagnetic torque Te of the single-machine endless bus system are shown in Fig. 4 a.

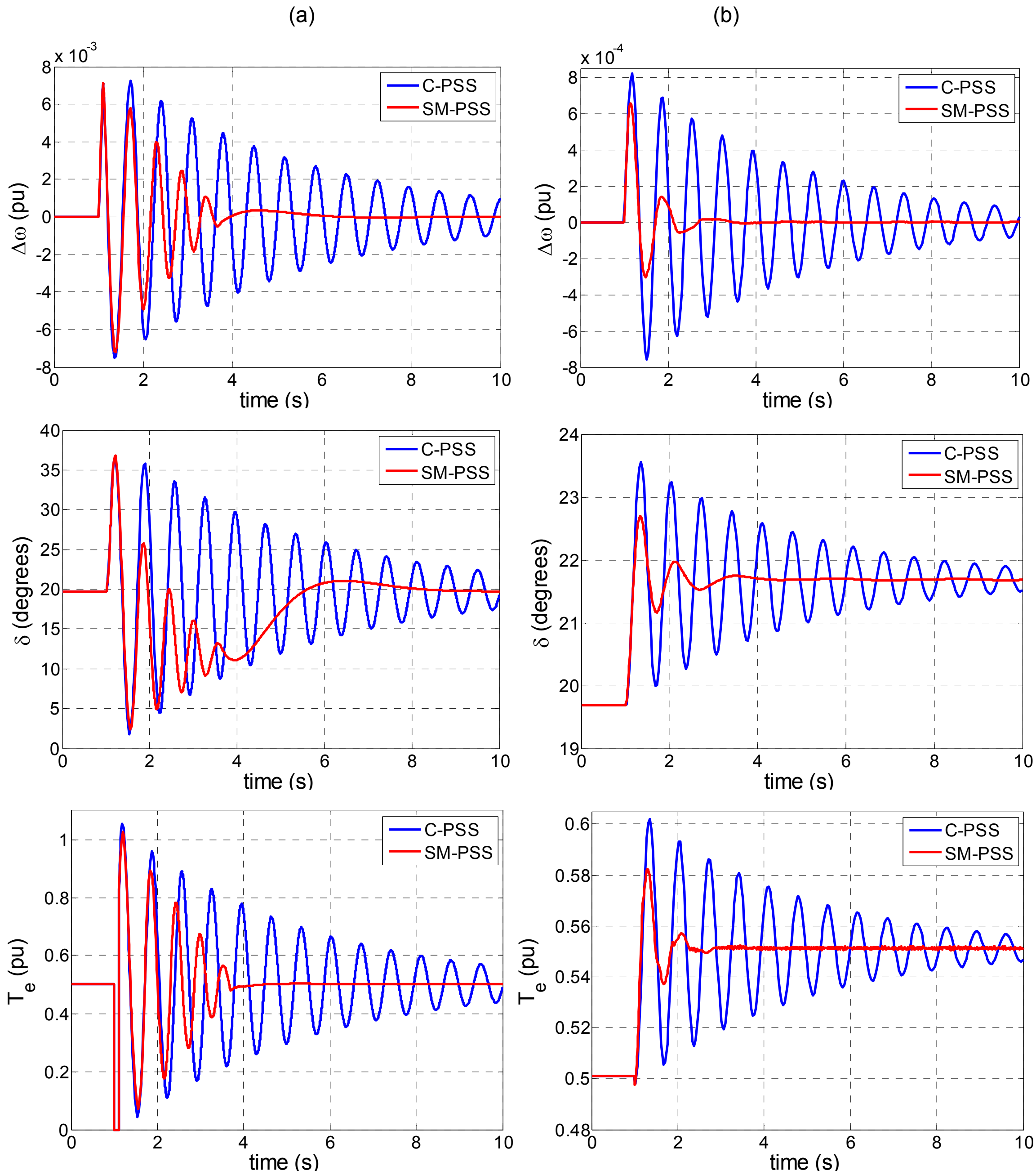

Fig. 5. System responses for Δω, δ and Te.
(a) Large fault condition, (b) Small fault condition

As can be understood from the responses in these figures, the proposed controller SM-PSS compared to the controller C-PSS, it has shorter settling time, providing the best damping characteristics to low-frequency oscillations and stabilizing the system more quickly.

- For small fault Condition: The performance of the proposed controller was confirmed by applying a 10 % *Tm* increase in mechanical power input at t = 1 s. In the event of a minor failure, in Fig. 4 b, it is shown the responses of *Δω*, *δ* and *Te* in respectively.

It can be seen from these results that the best response is obtained when the SM-PSS is used. The SM-PSS has stabilized the system with a smaller settling time and overshoot compared to C-PSS.

Conclusion

In this article a power system stabilizer design based on sliding mode controller is used to dampen the electromechanical oscillations and increase the stability of the power system.

The design was applied to a typical single-machine endless bus bar power system. The obtained results of the system for rotor angle and speed deviation show that the SM-PSS increases the stability and performance of the power system compared to C-PSS.

The results demonstrated that the proposed controller of power system stabilizer can guarantee the robust stability and performance of the power system under a wide range of system operating conditions. The results are promising and confirming the potential of this technic for optimal coordination of AVR and PSS design.

Authors:
Imene Dehiba, E-mail: de_imene@yahoo.fr; Mohamed Abid, E-mail: irecom_abid@yahoo.fr; Abdelghani Aissaoui, E-mail: irecom_aissaoui@yahoo.fr; Boubeker Dehiba, E-mail: deh_mas@yahoo.fr.

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