Asian Journal of Information Technology 6 (10): 1057-1063, 2007
ISSN: 1682-3915

Observer Based Intelligent Power System Stabilizer

[1]N. Mohamed Harmas, [1]Merzouki Abdelaziz and [2]A. Hamdi-Cherif
[1]Département d'Électrotechnique, Université Ferhat Abbas, Sétif, Algeria
[2]Department of Computer Science, Al-Qasim University, Saudi Arabia

Abstract: An intelligent power system stabilizer FSMC-PSS relying on a fuzzy supervisor, continuously modulating the action of a fuzzy logic controller and a robust sliding mode controller, is developed to add excitation control to a power system with the objective of rapidly eliminating low frequency oscillations. Thus a robust approach, here fuzzy technique, in conjunction with a robust sliding mode procedure, is used to perform as an intelligent power system stabilizer. Combining advantages of both techniques the fuzzy supervisor controls the action of the two controllers which rely on a linear state observer to allow for poles placement in the sliding mode through state feedback. Robust sliding mode control is fully used whenever the system state trajectory is faraway from the sliding surface and continually modulated with fuzzy control taking gradually over when near the desired manifold thus greatly reducing chattering inherently proper to discontinuous control action. A fourth order model of a power system representing a single synchronous generator connected to an infinite bus through a double transmission line is presented in order to assess performance enhancements compared to those brought by either approach alone. Simulation studies of the proposed controller showed that the controller was effective in damping electromechanical oscillations.

Key words: Intelligent techniques, fuzzy logic stabilizer, PSS, sliding mode controller, power system

INTRODUCTION

Increasing operating and maintenance costs as well as continuously increasing demand on electrical energy has forced power companies to call upon all of their installed capacities despite rapidly fluctuating operating conditions. These reasons and the apparition of low frequency local and inter area oscillations hindering power flow have caused renewed interest in robust PSS techniques. Among techniques to enhance power flow, power system stabilizers have been used with field proven efficient for more than 80 years resulting in savings of millions of dollars (Berube *et al*., 1999). PSS have been installed in Canada and the USA in the early 60s which witnessed the expansion of system excitation task by using auxiliary stabilizing signals to control the field voltage to damp system oscillations in addition to the terminal voltage error signal. This part of excitation control has been coined as PSS, i.e. power system stabilizer (Kundur, 1994). Early PSS were basically static phase lead compensators inserted ahead of the regulator-exciter to supply supplementary stabilizing signals to compensate for the large phase lag introduced by the excitation system. Yet rapidly fluctuating loading conditions require a more intelligent and more robust approach. Advances in so called intelligent control (Passino, 1996) have thrusted forward their applications in power system control driven by progress in computing technology as well as theoretical advances in methodologies based on human intelligence emulating algorithms such as fuzzy systems, artificial neural networks, genetic algorithms…etc.

New trends were set in PSS leading to a profusion of papers amid which Kothari *et al*. (1993) who developed a variable structure power system stabilizer with desired eigenvalues in the sliding mode, Hariri and Malik (1995) combined fuzzy control with learning propriety of neural network to elaborate a PSS which could lead the equilibrium state to be trapped into local minima, Hoang and Tomosovic (1996) introduced an adaptive fuzzy PSS with 49 fuzzy rules, Abido and Abdel-Magid (2000) made use of an evolutionary programming algorithm to calculate the optimal values of a classical lead-lag PSS, Rashidi *et al*. (2003) in which authors proposed to adapt the gain of the discontinuous component of the control signal used in the sliding mode controller using a fuzzy inference system augmented by linear state feedback applied to a sliding surface with an integral term. Elshafei *et al*. (2005) proposed power system stabilization using fuzzy logic and direct adaptive technique, Hossein-Zadeh and Kalam (2002) developed an indirect adaptive indirect fuzzy, Elshafei *et al*. (2005) extended the direct adaptive fuzzy approach to include stabilization of multi-machine power systems.

Corresponding Author: N. Mohamed Harmas, Département d'Électrotechnique, Université Ferhat Abbas, Sétif, Algeria

An intelligent robust PSS combining advantages of fuzzy logic and sliding mode control calling upon a fuzzy supervisor to continuously modulate their respective control action is proposed in this study. First a fuzzy stabilizer is developed as well as a sliding mode PSS using pole placement technique in the sliding mode (Kothari *et al.*, 1993) are elaborated to enhance oscillations damping in a single machine power system connected to an infinite bus through a double line feeder. Continuous action of both separate stabilizers is managed through a fuzzy supervisor that enforces SMC action when away from the equilibrium point and emphasizes FLC action when near the steady-state situation greatly reducing chattering.

This study introduces briefly a single machine power system followed by a presentation of basic notions of fuzzy and sliding mode control and applied to power system stabilization. Simulation of a fuzzy PSS and a SMC-PSS of a power system, under normal load, is presented.

A fuzzy supervisory controller is then added to modulate control action of the previous developed PSS, discussion of simulation is then presented and results are compared to FPSS and to SMC-PSS to assess chattering reduction and performance enhancements followed by this study.

Single machine power system: A small signal fourth order model of a synchronous machine connected to an infinite bus through a double transmission line, with assumedly negligible resistance, is given in space-state form, with the state vector, in which $\Delta\omega$ and $\Delta\delta$ $\Delta e'_q$ and Δe_{fd} represent respectively the angular velocity, torque angle, quadrature transient voltage and exciter output variations.

$$x(t) = \begin{bmatrix} \Delta\omega & \Delta\delta & \Delta e'_q & \Delta e_{fd} \end{bmatrix} \quad (1)$$

Thus the following fourth order model, easily derived from the linearized state equations given below Lee and Park (1998) is used throughout this study:

$$\Delta\dot{\omega}(t) = \frac{k_1}{M}\Delta\delta(t) - \frac{k_2}{M}\Delta e'_q(t) \quad (2a)$$

$$\Delta\dot{\delta}(t) = \omega_0 \Delta\omega(t) \quad (2b)$$

$$\Delta\dot{e}_q(t) = -\frac{k_4}{T'_{do}}\Delta\delta(t) - \frac{1}{T'_{do}k_3}\Delta e'_q(t) + \frac{1}{T'_{do}}\Delta e_{fd}(t) \quad (2c)$$

$$\Delta\dot{e}_{fd}(t) = -\frac{k_4 k_5}{T_A}\Delta\delta(t) - \frac{k_6}{T_A}\Delta e'_q(t) - \frac{1}{T_A}\Delta e_{fd}(t) + \frac{k_A}{T_A}u_{PSS} \quad (2d)$$

The model of a connected synchronous machine with exciter and voltage regulator, including operating point dependent K_i parameters (Kundur, 1994) is shown in Fig. 1.

U_{PSS} is the control signal elaborated by PSS to help damp the low frequency electromechanical oscillations inherent to power systems.

Parameter values and nomenclature are given in the Appendix.

In the next study, a fuzzy logic PSS is developed following a brief introduction of fuzzy logic control notions.

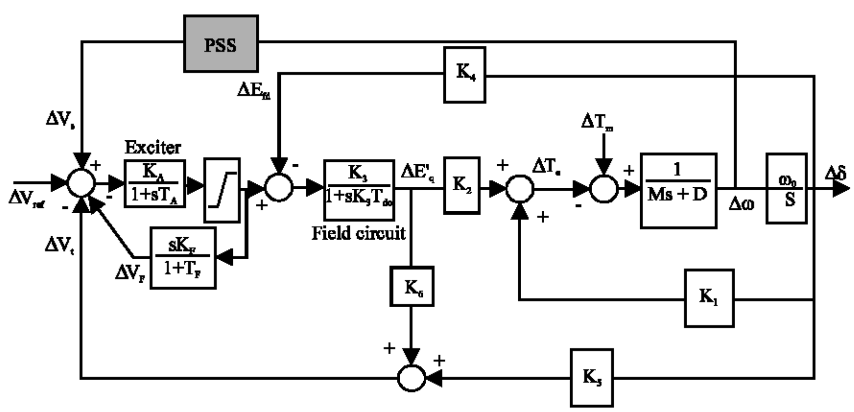

Fig. 1: Small perturbation model of connected synchronous machine including operating-point-dependent K_i factors and PSS

Appendix

System parameters used in simulation (Lee and Park, 1998)

For normal load conditions
$k_1 = 0.5698$, $k_2 = 0.9709$, $k_3 = 0.6584$,
$k_4 = 0.5233$, $k_5 = -0.0500$, $k_6 = 0.8454$
$P = 0.75$; $Q = 0.02$; $V_{to} = 1.05$
$M = 9.26$; $D = 0$; $T'_{do} = 7.76$; $w_o = 377$
$x_d = 0.97$; $x'_d = 0.55$
$K_A = 50.0$; $T_A = 0.05$
$X = 0.997$; $G = 0.249$; $B = 0$

FUZZY LOGIC CONTROL

Fuzzy logic control is a well known aspect of fuzzy set theory developed by Zadeh (1965) and applied for the first time in control by Mamdani (1974). Since then fuzzy logic has seen its use encompass many industrial domains in which fuzzy logic controllers are basically designed based on field experience.

Robust, not requiring plant model, insensitive to parameter variations, fuzzy logic technique is used in this paper to synthesize first a fuzzy power system stabilizer FPSS, with deviation variation from synchronous speed of the machine and its first derivative as its two inputs and outputs the supplementary signal added to the excitation system with the aim of enhancing low frequency rotor oscillations damping.

Only the main traits of FLC basic methodology, readily available in much of related literature (Zedeh, 1965; Mamdani, 1974) will be recalled in this study.

Basically a fuzzy logic controller, FLC, is designed by choosing relevant linguistic variables followed by a choice of a set of rules and a fuzzy reasoning process and has the following structure (Fig. 2).

Fuzzy logic is an approach that mimics human intelligence permitting to translate expert knowledge into linguistic rules used to activate FLC action. Fuzzy rules, for Takagi-Sugeno type controller, are generally given as follows:

Fuzzy rule *j* is given by:

$$\text{IF } e \text{ is } S_0^j \text{ AND } \dot{e} \text{ is } S_1^j \text{ THEN } u_{FLC} = f^j(e, \dot{e})$$

Where, S^j_0 and S^j_1 are fuzzy sets for FLC input variables e and $\dot{e}$, respectively and u_{FLC} its output, index j refers to the j^{th} rule ,index i indicates the number of input variables and f^j (e, $\dot{e}$) a function of inputs and generally taken as a singleton in adaptive control. Mamadani type fuzzy controller relies on fuzzy rules given by:

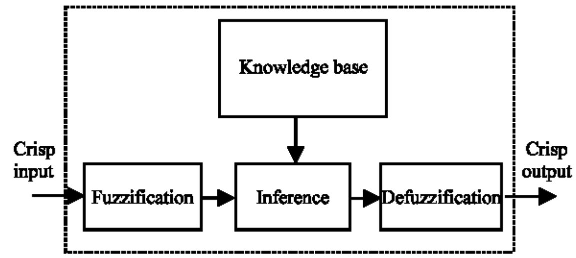

Fig. 2: Basic fuzzy logic controller

Table 1: FPSS inference table

e/ė	NB	NS	Z	PS	PB
NB	NB	NB	NB	PS	Z
NS	NB	NS	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

$$\text{IF } e \text{ is } S_0^j \text{ AND } \dot{e} \text{ is } S_1^j \text{ THEN } u_{FLC} \text{ is } S_2^j$$

Where S^j_0 , S^j_1 and S^j_2 are respectively fuzzy sets for e, $\dot{e}$ and u.

We first develop, a FPSS, a fuzzy logic controller using angular velocity variation and the variation of the acceleration of the machine as inputs, with 5 gaussian membership functions each with the control signal u_{FLC} as output. Control signal u_{FLC} is obtained using a symmetrical set of 25 fuzzy rules, which is obtained from expert knowledge and simulation of the underlying system. In non adaptive systems fuzzy if-then rules are totally based on operator expertise and/or based on simulation.

Table 1 depicts the 25 rules used to modulate symmetrically its output u_{FLC} as a function of its inputs.

A linear sate variable observer is used in conjunction with fuzzy, sliding mode and the proposed PSS. If the state and output equations are given as:

$$\dot{x} = Ax(t) + Bu(t); x_0 \tag{3}$$

$$y = Cx(t) \tag{4}$$

X(t) represents the state vector, y the output and where A , B and C represent, respectively the state, the control and the output matrices. Assuming that (A, C) is observable and (A,B) controllable, the observer state equation may be written as Utkin (1997):

$$\dot{\hat{x}} = A\hat{x}(t) + Bu(t) + LC(\hat{x}(t) - x(t)) \tag{5}$$

$$= (A - LC)\hat{x}(t) + Bu(t) + Ly(t) \tag{6}$$

In wich $\hat{x}(t)$ is the estimated state vector L is the observer gain obtained as:

$$L = PC^T R^{-1} \tag{7}$$

Where, Q and R are designer specified positive definite matrices and P is the definite positive matrix solution of the following ARE:

$$AP + PA^T - PC^T R^{-1} CP + Q = 0 \tag{8}$$

SLIDING MODE CONTROL

Sliding mode is a technique which basically consist in forcing system trajectories to intersect a predefined sliding surface on the state space and to remain on it, motion coined as sliding mode (Utkin, 1997). Robustness of sliding mode control has become a well recognized fact as early as 1969 (Drazenovic, 1969). However, its major drawback, chattering, slowed its wide acceptance by control engineers until the advent of fast switching electronics devices and research works such as Utkin (1978), Hung *et al.* (1993), Slotine and Li (1991) and Edwards and Spurgeon (1998) that turned sliding mode techniques into a well established tool of robust control.

Sliding mode control basics:

Given a system defined by:

$$\dot{x} = Ax(t) + Bu(t) + z(x,t); x_0 \tag{9}$$

Where, $A \in R^{n\times n}$ and $B \in R^{m\times n}$ represent the nominal system matrices and x(t) is an $n\times 1$ state vector and u(t) is an $m\times 1$ control vector , $z(x, t) \in R^{n\times 1}$ represents lumped bounded perturbations and uncertainties such that matching conditions are satisfied so we can write: z(x, t) = Bw(x, t) and assuming that w(x, t) is bounded such that:

$$|w(x,t)| \le v(x,t) \tag{10}$$

Sliding mode control is a two step design process: first desired dynamics surface on which sliding motion should occur is set followed by formulation of control law to force system trajectories to be attracted and maintained on the sliding surface.

Typically a sliding surface is of the form:

$$S = G\hat{x}(t) \tag{11}$$

Where: $G \in R^{n\times 1}$ is a constant vector.

Maintaining desired dynamic motion of the controlled nominal system on the surface, a control law u_E, so called equivalent control, must enforce the following condition:

$$\dot{S}(x,t) = 0 \tag{12}$$

which, assuming that $(GB)^{-1}$ exists, leads for the nominal system and a stationary surface to:

$$u_E = -k_E \hat{x}(t) \tag{13}$$

in which $k_E = (GB)^{-1}$ is a constant gain equivalent to conventional state feedback or optimal control gain and is obtained through poles placement in the sliding phase technique (Kothari *et al.*, 1993) thus allowing for G to be calculated.

A fast switching control component must then be added to the equivalent control to uphold the so called reaching condition and to permit sliding to occur.

Let a classic Lyapunov function candidate be:

$$V = \frac{1}{2} S^T S \le 0 \tag{14}$$

whose derivative along system state trajectories gives:

$$\dot{V} = S^T \dot{S} \le 0 \tag{15}$$

$$\dot{V} = S^T \left(\frac{\partial S}{\partial x}(Ax + B(u + w)) + \frac{\partial S}{\partial t}\right) \tag{16}$$

for a stationary surface, using:

$$u_{smc} = u_E + u_d \tag{17}$$

results in satisfying asymptotic stability despite bounded uncertainties z(x, t), if u_d, a discontinuous control signal, is chosen as:

$$u_d = -v\,\mathrm{sgn}(S^T GB) \tag{18}$$

Thus total SMC control is given by:

$$u_{smc} = -(GB)^{-1}(GA)\hat{x}(t) - v \times \mathrm{sign}(S^T GB) \tag{19}$$

A sliding mode PSS is synthesized for a single machine power system and simulation results for conventional and SMC-PSS shown in Fig. 3 are compared. Robustness of the latter scheme is only flawed by inherent chattering present in the control signal.

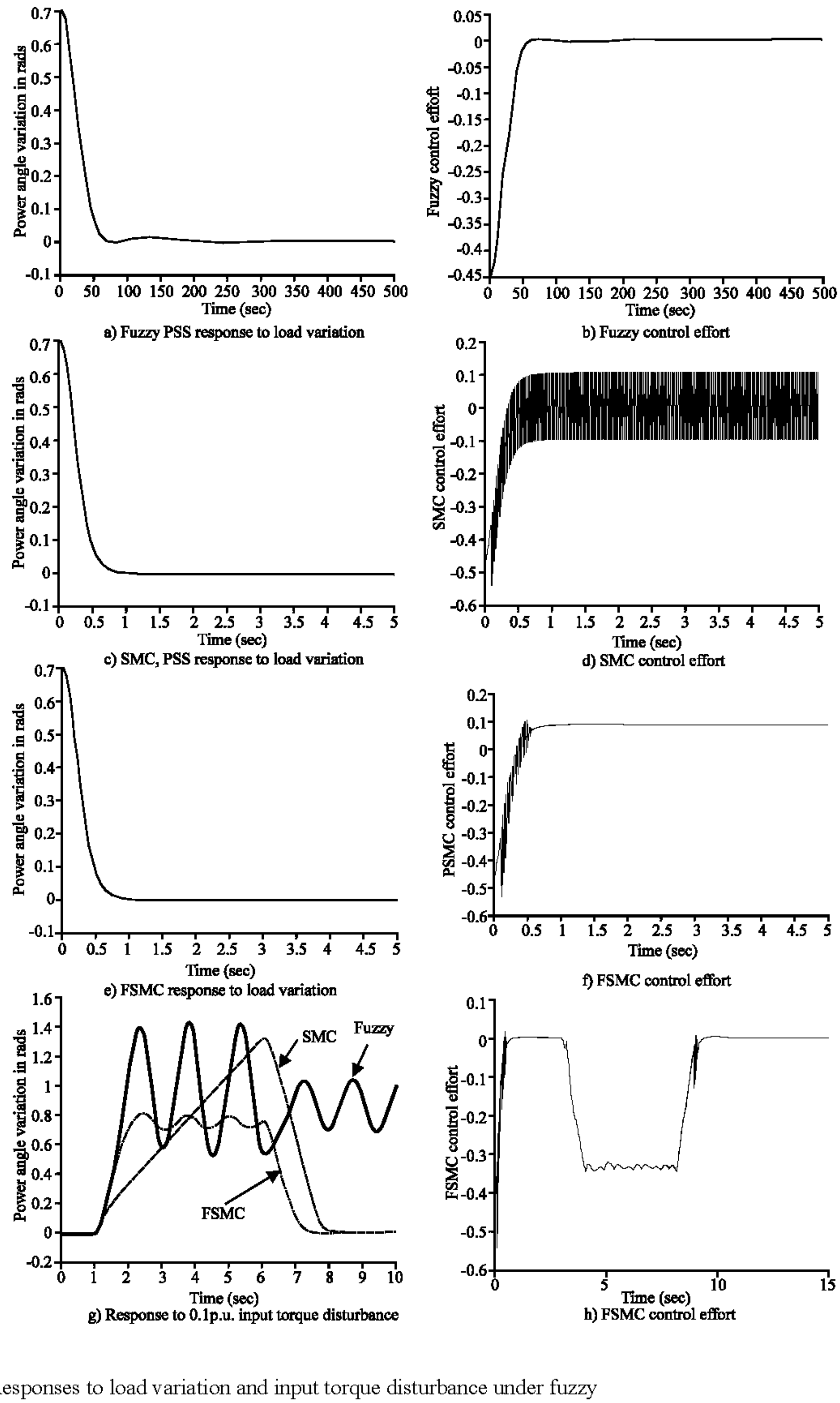

Fig. 3: Responses to load variation and input torque disturbance under fuzzy

INTELLIGENT POWER SYSTEM STABILIZER

Both presented controllers are robust yet sliding mode control requires knowledge of the system matrices and necessitates fast control activity which can sometimes damage actuators. On the other hand, fuzzy control, although not as robust, doesn't require full knowledge of system parameters and can be used to reduce chattering proper to sliding mode control.

It is desired to elaborate a robust PSS such that response performance doesn't deteriorate in presence of bounded uncertainties yet with a smooth control law free of excess chatter despite ever present uncertainties. It is therefore proposed to use a fuzzy supervisor to continuously control action of both controllers according to the following control law which guaranties asymptotic stability.

$$u_{PSS} = \alpha\ u_{FLC} + (\alpha - 1)u_{smc} \quad 0 < \alpha < 1 \qquad (20)$$

The main idea being to put to full use the sliding mode controller when the system is away from its equilibrium point and to modulates it as the error gets smaller to switch to practically total fuzzy control when the equilibrium point is about to be reached with stability guaranteed by Wong's theorem (Wong *et al*., 1998) modified to include a fuzzy controller as to guarantee (15) since: $0 < \alpha < 1$

$$\text{Min}\ (u_{smc}, u_{FLC}) < u_{PSS} < \text{Max}\ (u_{smc}, u_{FLC}) \qquad (21)$$

The proposed PSS, using a linear sate observer, applied to a single machine power system is shown in Fig. 4.

Simulation for a single machine power system under a 0.1 p.u. disturbance input torque applied at t = 3s for 5s is used to assess performances and robustness. Results for Fuzzy, SMC and FSMC applied PSS are shown in Fig. 3.

Figure 3 a and b illustrate good performances of fuzzy PSS on load variation, causing a 0.7 radian excursion of torque angle variation. Better performance results are obtained using SMC (Fig. 3c) except that control effort exhibit strong undesirable chattering shown in Fig. 3d.

Similar results are obtained with proposed FSMC yet with considerable chattering reduction in the control signal required.

Next robustness of the three methods is compared in the presence of a 0.1p.u. input torque perturbation occurring at 3 seconds and lasting for 5 sec. As shown in Fig. 3g, FSMC with state observer and fuzzy supervisor proposed PSS confirms the soundness of the approach

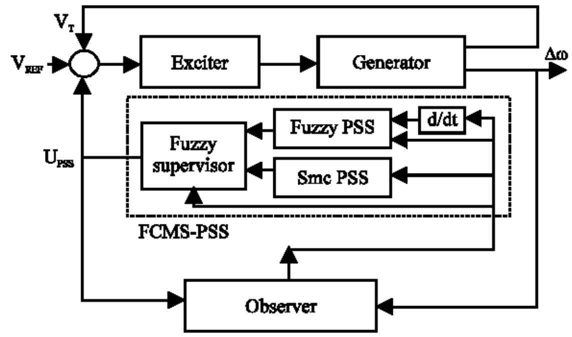

Fig. 4: Proposed FSMC-PSS with state observer

for it rapidly eliminates the oscillations whereas the system enters into sustained oscillations under fuzzy PSS. Compared to SMC stabilizer performances. Figure 3g clearly indicates that steady state is reached earlier in FSMC than when using SMC and with much less chatter in its control effort as illustrated in Fig. 3h due to the use of the fuzzy supervisor control which mimics an intelligent operator.

CONCLUSION

In this study, we present a state observer based power system stabilizer FSMC-PSS that relies on a fuzzy logic supervisor enabling a soft transition between two robust PSS, Fuzzy and SMC stabilizers to overcome low oscillations inherent to power systems operation. Simulation for two different operating conditions seem to indicate that the approach puts to good use the advantages of the two techniques mentioned while discarding, to some extent, their inherent limitations. Simulation test showed the effectiveness of the robustness of the proposed intelligent stabilizer.

REFERENCES

Abido, M.A. and Y.L. Abdel-Magid, 2000. Design of power system stabilizers using evolutionary programming. IEEE Transaction on Energy Conversion, Vol. 17.

Bérubé, G.R., L. Hajagos and R. Beaulieu, 1999. Practical Utility Experience with Application of Power System Stabilizers. IEEE PES Working Group Panel Presentation on Power System Stabilizers.

Drazenovic, B., 1969. The invariance conditions in Variable Structure Systems. Automatica, 5: 287-295.

Edwards, C. and K.S. Spurgeon 1998. Sliding Mode Control, Taylor and Francis.

Elshafei, A.L., K. El-Metwally and A.A. Shaltout, 2005. A variable structure adaptive fuzzy logic stabilizer for single and multi-machine power systems. Control Engineering Practice, Elsevier, 13: 413-423.

Elshafei, A.L., K. El-Metwally and A.A. Shaltout, 2005. A variable structure adaptive fzzy logic stabilizer for single and multi-machine power systems. Control Engineering Practice, Elsevier, 13: 413-423.

Hariri, A. and O.P. Malik, 1995. Adaptive-Network-Based Fuzzy Logic Power System Stabilizer. IEEE Wescanex 95, Proceedings Wescanex, pp: 111-116.

Hoang, P. and K. Tomosovic, 1996. Design and Analysis of an Adaptive Fuzzy Power Syste Stabilizer. IEEE Transaction Energy Conversion, Vol. 11.

Hossein-Zadeh, N. and A. Kalam, 2002. An indirect adaptive fuzzy-logic power system stabilizer, Elsevier. Elec. Power and Energy Sys., 24: 837-842.

Hung, J.Y., W. Gao and J.C. Hung, 1993. Variable Structure Control: A Survey, IEEE. Trans. Ind. Elec., 40: 2-21.

Kothari, M.L., J. Nanda and K. Bhattacharya, 1993. Design of variable structure power system stabilizers with desired eigenvalues in the sliding mode. IEEE. Proc. Generation Trans. Distribut., 140: 263-268.

Kundur, P., 1994. Power System Stability and Control, McGraw Hill.

Lee, S.S. and J.K. Park, 1998. Design of power system stabilizer using observer/sliding mode, observer/ sliding mode model following and H?/sliding mode controllers for small signal stability study. Elec. Power Energy Sys. Elsevier Sci. Ltd., 20: 543-553.

Mamdani, E.H., 1974. Application of fuzzy algorithms for control of simple dynamic plant. Proc. IEEE., 121: 1585-1588.

Passino, K.M., 1996. Intelligent Control, The Control Handbook, W.S. Levine. CRC. Press, pp: 994-998.

Rashidi, F., M. Rashidi and H. Amiri, 2003. An adaptive fuzzy sliding mode control for power system stabilizer. Industrial Electronics Society, IECON. The 29th Ann. Conf. IEEE., 1: 626-630.

Slotine, J.J. and W. Li, 1991. Applied nonlinear control, P. Hall.

Utkin, V.I., 1997. Variable Structure Systems with Sliding Modes. IEEE. Trans. Automatic Control, AC-22: 212-222.

Utkin, V.I., 1978. Sliding Modes and their Application in Variable Structure Systems, Mir.

Wong, L.K., F.H.F. Leung and P.K.S. Tam, 1998. Combination of sliding mode controller and PI controller using fuzzy logic controller. In: IEEE. Int. Conf. Fuzzy Sys., pp: 296-301.

Zadeh, L., 1965. Fuzzy Sets, Inform. Control, 8: 338-353.