Sliding mode control without reaching phase for multimachine power system combined with fuzzy PID based on PSS

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Abstract: - The objective of this paper is to design a nonlinear robust controller for the multimachine power system. We present in this study a sliding mode control method without the reaching phase by modifying the terms of the output tracking error combined with the fuzzy Proportional Integral Derivative based on Power System Stabilizer (FPID-PSS). The Mamdani fuzzy inference is used in this study to find the optimal values of the three parameters (K_p, K_i, K_d) of (PID -PSS). The proposed approach is designed to eliminate completely the reaching phase and to enhance the stability and the dynamic response of the multimachine power system. In order to test the effectiveness of the proposed method, the simulation results show the damping of the oscillations of the angle and angular speed with reduced overshoots and quick settling time.

Key-Words: - Fuzzy Logic, Reaching Phase, Sliding Mode Control, Proportional Integral Derivative, Power System Stabilizer, Multimachine Power System.

1 Introduction

The stability of power systems is one of the most important aspects in electric system operation. The size and complexity of modern electric power systems necessitates the construction of reduced-order dynamic models [1]. Determination of transient stability is one of the major items of power system operation and planning [2].

Most controllers PSSs used in electric power system employ the linear control theory approach based on a linear model of a fixed configuration of the power system and thus tuned at a certain operating condition. The fixed parameter PSS, called conventional PSS, is widely used in power systems, it often does not provide satisfactory results over a wide range of operating conditions [3]. To overcome these drawbacks, a lot of different techniques have been reported in the literature pertaining to coordinated design problem of the PSS [4].

The proposed controller in this paper consist of the combination of the sliding mode control without reaching phase with the fuzzy proportional integral derivative based on power system stabilizer (FPID-PSS). The main objective of the Mamdani fuzzy inference method is to adjust the correctives gains for the optimal setting of controller parameters PID-PSS which provide a good performance and better results.

The Sliding Mode Control (SMC) is essentially a switching feedback control where the gains in each feedback path switch between two values according to some rule [9]. The switching feedback law drives the controlled system's state trajectory in to specified surface called the sliding surface which represents the desired dynamic behavior of the controlled system [5]. The SMC is used in this paper due to its disturbance rejection, strong robustness subject to system parameter variations, uncertainties and external disturbances.

During the reaching phase, the tracking error cannot be controlled directly and the system response is sensitive to parameter uncertainties [10]. Several methods have been proposed to completely eliminate the reaching phase [6], [11], [18]. To accomplish this, the general exponential form of tracking error is introduced. A modified sliding mode control is used to eliminate the reaching phase, and ensures optimal tracking subject to minimal control effort.

The objective of the proposed approach is to compensate the fluctuations in multiple modes of oscillations and eliminates the reaching phase which directly influences the tracking errors in the multimachine power system. This method guarantees the robust performance for damping low frequency oscillations.

This paper is organized as follows: The nonlinear mathematical model of the multimachine power system represented by state-space is proposed in section 2. The PID based on PSS controller is described in Section 3. The fuzzy PID-PSS is designed in which the gains of this controller are tuned in section 4. The proposed control method is applied in Section 5. The performances of the proposed method according to robustness tests are shown through simulations of the multimachine power system in Section 6. Finally, conclusion is given in Section 7.

2 Multimachine power system

Under some standard assumptions, the dynamics of n interconnected generators through a transmission network can be described by the classical model with flux decay dynamics. The network has been reduced to internal bus representation assuming loads to be constant impedances and considering the presence of transfer conductance. The dynamical model of the ith machine is represented by the classical third order model [7]:

$$\begin{cases} \dot{\delta}_i = \omega_i - \omega_s \\ \dot{\omega}_i = \dfrac{\omega_s}{2H_i}\left(P_{m_i} - D_i\left(\omega_i - \omega_s\right) - E'_{qi} I_{qi}\right) \\ \dot{E}'_{qi} = \dfrac{1}{T'_{di}}\left(E_{fi} - E'_{qi} - \left(X_{di} - X'_{di}\right) I_{di}\right) \end{cases} \tag{1}$$

I_{qi} and I_{di} represent currents in d–q reference frame of the ith generator, E'_{qi} is the transient EMF in the quadrature axis, $E_{fi}(t)$ is the equivalent EMF in the excitation coil, X_{di} and X'_{di} are direct axis reactance and direct axis transient reactance, respectively, where :

$$\begin{cases} I_{qi} = G_{ii}E'_{qi} + \sum\limits_{j=1, j\neq i}^{n} E'_{qi} \begin{Bmatrix} G_{ij}\cos\left(\delta_j - \delta_i\right) \\ -B_{ij}\sin\left(\delta_j - \delta_i\right) \end{Bmatrix} \\ I_{di} = -B_{ii}E'_{qi} - \sum\limits_{j=1, j\neq i}^{n} E'_{qi} \begin{Bmatrix} G_{ij}\sin\left(\delta_j - \delta_i\right) \\ +B_{ij}\cos\left(\delta_j - \delta_i\right) \end{Bmatrix} \end{cases} \tag{2}$$

P_{m_i} is the mechanical input power assumed to be constant, D_i is the damping factor; all parameters are in p.u. H_i, represents the inertia constant, in seconds; T'_{di} is the direct axis transient short circuit time constant, in seconds; δ_i is the rotor angle, in radians; ω_i represents the relative speed, $\omega_s = 2\pi f$ is the synchronous machine speed, in rad/s; G_{ij} and B_{ij} are the ith row and jth column element of the nodal conductance matrix and nodal susceptance matrix respectively, which are symmetric, at the internal nodes after eliminating all physical buses in p.u.. We consider $E_{fi}(t)$ as the input of the system [7]. The state representation of the ith machine of a multimachine power system can be written in the following form:

$x_i = \left[x_{i1}, x_{i2}, x_{i3}\right]^T = \left[\delta_i, \omega_i, E'_{qi}\right]$ For i = 1, 2 ... n, represents the state vector of ith subsystem, and the control applied is given by:

$$u_i = \frac{1}{T'_{di}} E_{fi} \tag{3}$$

$$\begin{aligned} \dot{x}_{i1} &= x_{i2} \\ \dot{x}_{i2} &= f_{i1}(X) \\ \dot{x}_{i3} &= f_{i2}(X) + u_i \end{aligned} \tag{4}$$

Where

$$\begin{cases} f_{i1}(X) = A_i - d_i x_{i3} \sum\limits_{j=1, j\neq i}^{n} x_{j3} \begin{Bmatrix} G_{ij}\cos\left(x_{j1} - x_{i1}\right) \\ -B_{ij}\sin\left(x_{j1} - x_{i1}\right) \end{Bmatrix} \\ f_{i2}(X) = -e_i x_{i3} + h_i \sum\limits_{j=1, j\neq i}^{n} x_{j3} \begin{Bmatrix} G_{ij}\sin\left(x_{j1} - x_{i1}\right) \\ +B_{ij}\cos\left(x_{j1} - x_{i1}\right) \end{Bmatrix} \end{cases} \tag{5}$$

With $A_i = a_i - b_i x_{i2} - c_i x_{i3}^2$

And

$$a_i = \frac{\omega_s}{2H_i} P_{m_i} \;\; ; \; \mathrm{b}_i = \frac{\omega_s}{2H_i}\mathrm{D}_i \;\; ; \; \mathrm{c}_i = \frac{\omega_s}{2H_i} G_{ii}$$

$$\mathrm{d}_i = \frac{\omega_s}{2H_{i\,i}} \;\; ; e_i = \frac{\left(1 - \left(X_{di} - X'_{di}\right) B_{ii}\right)}{T'_{di}}; \;\; \mathrm{h}_i = \frac{X_{di} - X'_{di}}{T'_{di}}$$

3 PID based on PSS design

Power System Stabilizer (PSS) is designed to minimize the power system oscillations after a small or large disturbance so as to improve the power system stability. The transfer function of the ith PSS is given by [8]:

$$u_{pssi} = K_{pss_i} \frac{sT_{Wi}}{1+sT_{Wi}} \left(\frac{(1+sT_{1i})(1+sT_{3i})}{(1+sT_{2i})(1+sT_{1i})} \right) \Delta\omega_i \qquad (6)$$

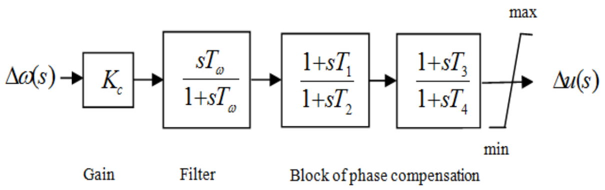

Fig. 1: Block diagram of the Conventional Power System Stabilizer.

Where K_{PSS_i} is the PSS gain, T_{wi} Washout Time constant and $\{T_{1i},\ T_{2i},\ T_{3i},\ T_{4i}\}$ are the Time constants.

Time Constants $T_{3i} = T_{3i}$, $T_{2i} = T_{4i}$, Identical Phase Compensator Block.

The block diagram of the conventional PSS is shown in fig. 1, in which case the generator rotor speed deviation is used as the only stabilizing signal. The Conventional PSS consists of an amplifier, a washout filter and two lead-lag compensators [8].

In this section we present the PID-PSS for damping the oscillations in multimachine power system. A set of PSS parameters which give good system performance under a certain operating condition may not give equally good result [12]. To have good performance of PSS under different conditions, Proportional Integral Derivative (PID) based on PSS is presented.

The supplementary signal for each machine based on PID control law takes the following form [13]:

$$u_i = k_{p_i} \Delta\omega_i + k_{i_i} \int_0^t \Delta\omega_i \, dt + k_{d_i} \frac{d\Delta\omega_i}{dt} \qquad (7)$$

Where $\Delta\omega$ is the speed deviation of the machine and k_p, k_i and k_d are the PID controller parameters, u_i is the supplementary stabilizing signal.

4 Fuzzy PID based on PSS control

The fuzzy controller design includes the definition the following parameters: Number of partitions of input space and output membership functions, rule base, inference method, fuzzification and defuzzification [3].

In this section, the Fuzzy PID-PSS controller is presented. More specifically, a fuzzy inference system is used to adjusting the gains of the controller in order to improve the performance of the controller.

The rules bases are in the following form [14]:

If e *is* A_i^m *and* $\dot{e}$ *is* B_i^m, *Then* α_i *is* C_i^m

Where A_i^m, B_i^m and C_i^m are fuzzy sets. Supposing the two input signals of the Fuzzy-PID-PSS controller are the error signal and the error deviation signal.

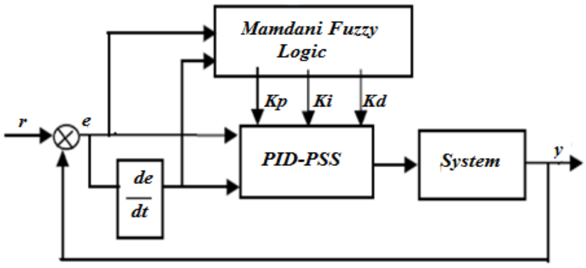

Fig. 2: Structure of the fuzzy-PID based on PSS controller.

The input ranges of the two signals $(e, \dot{e})$ are from [-0.01, 0.01]. For the rule base, the fuzzy variables input are defined by:

$(e, \dot{e}) = \{NB, NM, NS, Z, PS, PN, PB\}$

and $\{k_p, k_i, k_d\} = \{VVS, VS, S, M, B, VB, VVB\}$, are the fuzzy outputs. The membership functions for the inputs and the outputs variables are Gaussian.

The outputs ranges of the gains $\{k_{p_j}, k_{i_j}, k_{d_j}\}$ for j=1, 2, 3, of the three generators are from:

$k_{p_1} = [0,70];\ k_{i_1} = [0,7];\ k_{d_1} = [0,10]$

$k_{p_2} = [0,50];\ k_{i_2} = [0,5];\ k_{d_2} = [0,7]$

$k_{p_3} = [0,50];\ k_{i_3} = [0,10];\ k_{d_3} = [0,5]$

The membership functions for the inputs variables are given in Fig. 3 and Fig. 4.

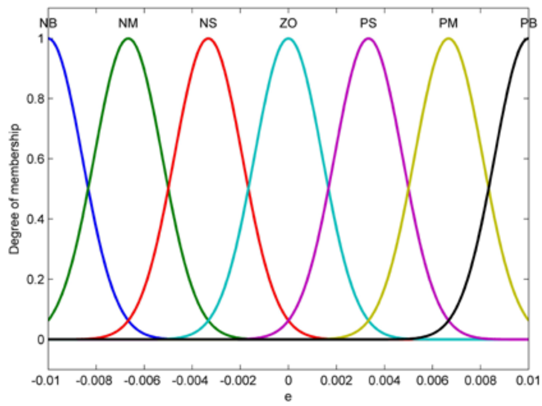

Fig. 3: Membership functions of error.

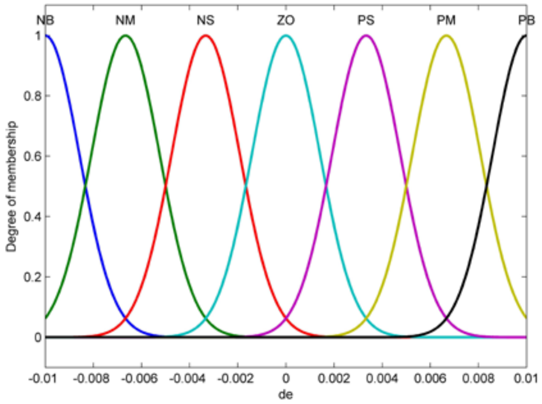

Fig. 4: Membership functions of change of error

The fuzzy rules are shown in table 1, table 2 and table 3 respectively [15].

Table 1: The fuzzy rule matrix of K_p

de \ e	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PM	PM	PS	Z	Z
NM	PB	PB	PM	PS	PS	Z	NS
NS	PM	PM	PM	PS	Z	NS	NS
Z	PM	PM	PS	Z	NS	NM	NM
PS	PS	PS	Z	NS	NS	NM	NM
PM	PS	Z	NS	NM	NM	NM	NB
PB	Z	Z	NM	NM	NM	NB	NB

Table 2: The fuzzy rule matrix of K_i

de \ e	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NM	NM	NS	Z	Z
NM	NB	NB	NM	NS	NS	Z	Z
NS	NM	NM	NS	NS	Z	PS	PS
Z	NM	NM	NS	Z	PS	PM	PM
PS	NM	NS	Z	PS	PS	PM	PB
PM	Z	Z	PS	PM	PM	PB	PB
PB	Z	Z	PS	PM	PM	PB	PB

Table 3: The fuzzy rule matrix of K_d

de \ e	NB	NM	NS	Z	PS	PM	PB
NB	PS	NS	NB	NB	NB	NM	PS
NM	PS	NS	NB	NM	NM	NS	Z
NS	Z	NS	NM	NM	NS	NS	Z
Z	Z	NS	NS	NS	NS	NS	Z
PS	Z	Z	Z	Z	Z	Z	Z
PM	PB	PS	PS	PS	PS	PS	PB
PB	PB	PM	PM	PM	PS	PS	PB

5 Proposed control design

5.1 Sliding mode control without reaching phase

The sliding mode controller with different positive characteristics including the robustness against the parameter changes, external disturbances, and uncertainties and quick dynamic response and simplicity of design is applicable in various nonlinear systems control [16]. It was successfully applied to electric motors, robot manipulators, power systems and power converters [9]. The response of a system controlled by a SMC includes two phases. The first phase is called the reaching phase [6]. During this phase, the controller drives the system response toward $S \to 0$. The second phase is the sliding phase, which is reached at $t = t_s$ such that $s \approx 0 \ \forall t \succ t_s$. In this section, we will present the principle of the sliding mode control without reaching phase. Let us consider the nonlinear system represented by the following state equation:

$$x^{(n)} = F(x) + G(x)u \tag{8}$$

Where $x = \left[x, \dot{x}, \dots\dots x^{(n-1)}\right] = \left[x_1, x_2, \dots\dots, x_n\right]$ is a state vector, $u \in R$ control input.

To avoid high control input gain, one introduces the following modified output tracking error [10].

We present the sliding mode control law that eliminates the reaching phase and achieves sliding at the onset of the motion. To realize this objective, we reformulate the output tracking error as follows [18]:

$$E_i(t) = e_i(t) - \eta_i(t) \tag{9}$$

Where the tracking error vector is: $e_i = [e_{1i}, e_{2i}, \dots\dots, e_{ni}] = \left[e_i, \dot{e}_i, \dots\dots, e_i^{(n-1)}\right]$

and $\eta_i(t)$ is designed to satisfy the following conditions [6]:

1- To make E small enough at the onset of the motion t=0.
2- Should rapidly vanish as the motion evolves at $t \succ 0$

A suggested $\eta_i(t)$ is given in the following exponential form:

$$\eta_i(t) = \gamma_i(t)\exp(Z_i(t)) \tag{10}$$

Using Taylor series:

$$\gamma_i(t) = \sum_{j=0}^{n-1} \frac{1}{j!}\gamma_i^{(j)}(t_0)(t-t_0)^j \tag{11}$$

$$\gamma_i^{(j)}(t_0) = \frac{d^j \gamma}{dt^j}(t = t_0) \tag{12}$$

$$Z_i(t) = -\beta_i t \tag{13}$$

$$\eta_i(t) = (q_{0i} + q_{1i}t + \dots + q_{n-1\,i}t^{n-1})\exp(-\beta_i t) \tag{14}$$

For $j = 0, 1\ldots n-1$, where β_i a positive constant, q_i is selected to satisfy condition -1- and $Z_i(t)$ is selected to satisfy condition -2-.

Expanding (9) by the Taylor's series leads to

$$E_i(t) = \sum_{j=1}^{n-1} \frac{1}{j!}\left(\left(e_i^{(j)}(0) - \eta_i^{(j)}(0)\right)t^j\right) + o(t^{n-1}) \qquad (15)$$

Where $o(t^{n-1})$ is an infinitesimal of higher order of t^{n-1}.

$$\eta_i^{(j)}(0) = e_i^{(j)}(0) \qquad (16)$$

Then (13) becomes $o(t^{n-1})$, i.e., Condition -1- is satisfied. The values of q_i can be obtained by resolving the equation set in (14).

We define a modified sliding surface as:

$$\bar{S}_i(t) = E_i^{(n-1)}(t) + k_{n-1_i} E_i^{(n-2)}(t) + \ldots + k_{1_i} E_i(t) \qquad (17)$$

This modified surface exponentially converges to the original one. Once the system state reaches the sliding surface it never leaves it. In this study, the relative degree is r=3 then, the switching function can be written as:

$$\bar{S}_i(t) = \ddot{E}_i(t) + k_{2i}\dot{E}_i(t) + k_{1i}E_i(t) \qquad (18)$$

Where

$$E_i(t) = e_i(t) - \eta_i(t) \qquad (19)$$

$$\eta_i(t) = (q_{0i} + q_{1i}t + q_{2i}t^2)\exp(-\beta_i t) \qquad (20)$$

$$\begin{aligned} e_{1i} &= \delta_i - \delta_{ir} = x_{i1} - x_{i1r} \\ e_{2i} &= \dot{e}_{1i} = x_{i2} \\ e_{3i} &= \dot{e}_{2i} = a_i - b_i x_{i2} - c_i x_{i3}^2 - d_i x_{i3} I_{q_i} \end{aligned} \qquad (21)$$

For i=1, 2 … n. Where $k_i = [k_{1i}, k_{2i}, 1]^T$ are the coefficients of the Hurwitz Polynomial:

$$h_i(\lambda) = \lambda^2 + k_{2i}\lambda + k_{1i} \qquad (22)$$

$$\begin{aligned} \dot{\bar{S}}_i(t) &= k_{1i}\dot{E}_i(t) + k_{2i}\ddot{E}_i(t) + \dddot{E}_i(t) \\ &= k_{1i}\dot{E}_i(t) + k_{2i}\ddot{E}_i(t) - \dddot{\eta}_i(t) + F_i(x) + G_i(x)u_i \end{aligned} \qquad (23)$$

If $F_i(x)$ and $G_i(x)$ are known, we can easily construct the modified sliding mode control:

$$u_i = u_{eq_i} + u_{smc_i} \qquad (24)$$

$$u_{eq_i} = \frac{-1}{G_i(x)}\left(k_{1i}\dot{E}_i(t) + k_{2i}\ddot{E}_i(t) - \dddot{\eta}_i(t) + F_i(x)\right) \qquad (25)$$

The equations representing the sliding mode control have been reformulated which the reaching phase is eliminated. The modified sliding mode control term is:

$$u_{smc_i} = \frac{-1}{G_i(x)}\alpha_i \,\mathrm{sgn}(\bar{S}_i) \qquad (26)$$

The control input u_{smc_i} to get the state δ_i to track δ_{ir}.

5.2 sliding mode control without reaching phase combined with Fuzzy PID-PSS

The control law used in this study is composed by three terms, the equivalent control u_{eq_i}, the robust term represented by the sliding mode controller without reaching phase u_{smc_i}, and the PID-PSS adapted by the mamdani fuzzy logic $u_{FPID-PSS}$.

$$u = u_{eq} + u_{smc} + u_{FPID-PSS} \qquad (27)$$

With α_i is the gain of sliding mode controller.

$$u_i = \frac{-1}{G_i(x)}\begin{pmatrix} k_{1i}\dot{E}_i(t) + k_{2i}\ddot{E}_i(t) \\ -\dddot{\eta}_i(t) + F_i(x) + \alpha_i sgn(\bar{S}_i) \end{pmatrix} + \tilde{k}_p\Delta\omega + \tilde{k}_i\int_0^t \Delta\omega\, dt + \tilde{k}_d \frac{d\Delta\omega}{dt} \qquad (28)$$

$\tilde{k}_p$, $\tilde{k}_i$, $\tilde{k}_d$ are the optimal value of proportional gain, integral gain and derivative gains, respectively.

The combination between the three controllers, the equivalent control and the modified sliding mode controller with the fuzzy PID based on PSS, enhances the damping of the oscillations and the stability of the network and eliminate completely the reaching phase.

6 Simulation of multimachine power system

To evaluate the performance of the proposed control, we performed the simulation in MATLAB for the three-machine nine-bus power system as in Fig. 5, with the aim to show the validity and the performance of the proposed controller. Detail of the system data are given in table 5 [17].

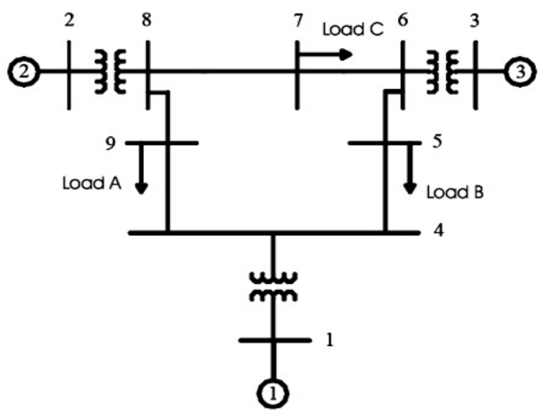

Fig. 5: Three-machine nine-bus power system.

The following equilibrium point:

$X_{ir} = (x_{i1r}, x_{i2r}, x_{i3r}) = [\delta_i \;\; \Delta\omega_i \;\; E'_{qi}]$ For $i = 1, 2, 3$ of the three-machine system is considered:

$x_{11r} = 0.0396$, $x_{12r} = 0$, $x_{13r} = 1.0566$
$x_{21r} = 0.3444$, $x_{22r} = 0$, $x_{23r} = 1.0502$
$x_{31r} = 0.2300$, $x_{32r} = 0$, $x_{33r} = 1.017$

The control parameters of sliding mode control used are $\alpha_i = 0.003$. The specified parameters of the PSS that are used in this study given in table 6 in appendix and the parameters of the PID controller are given in table 7 in appendix.
We present the parameters of the modified tracking error $E_i(t)$, we choose:
$\beta_1 = 0.5$; $\beta_2 = 3.35$; $\beta_3 = 2.6$

From the method in [11], one can make:

$$\begin{cases} \eta_i(0) = q_{0i} = x_{1i}(0) - x_{1ir}(0) \\ \dot{\eta}_i(0) = q_{1i} - \beta_i q_{0i} = \dot{x}_{1i}(0) - \dot{x}_{1ir}(0) \\ \ddot{\eta}_i(0) = 2q_{2i} - 2\beta_i q_{1i} + \beta_i^2 q_{0i} = \ddot{x}_{1i}(0) - \ddot{x}_{1ir}(0) \end{cases} \quad (29)$$

To demonstrate the performance and the robustness of the proposed method, two performance indices: the Integral of the Time multiplied Absolute value of the Error (ITAE) and the Integral of Time weighted Squared Error (ITSE) based on the system performance characteristics are being used as:

$$ITAE = \int_0^T t(|\Delta\omega_1| + |\Delta\omega_2| + |\Delta\omega_3|)dt \quad (30)$$

$$ITSE = \int_0^T \left(\Delta\omega_1^2(t) + \Delta\omega_2^2(t) + \Delta\omega_3^2(t)\right).t.dt \quad (31)$$

More than the values of the performance indices ITAE and ITSE are lower, the response of the system in time domain is better. Numerical results of these indices for all cases are presented in table 4.

Table 4: Performance indices of the controllers

	ITAE	ITSE
Proposed Control	0.0303	2.0851e-007
SMC&FPID-PSS	0.3186	6.2660e-006
SMC&PID-PSS	0.9038	1.8339e-005
PSS Control	3.5700	8.8233e-005

In order to review the validity and the robustness of proposed control, simulation studies are carried out for three machines nine bus. The aim in this section is to compare the performance of the proposed control (SMC without reaching phase & FPID-PSS) with (SMC & FPID-PSS), the (SMC & PID-PSS) and the PSS. The simulation results demonstrated that the proposed control is capable to guarantee the robust performance of the multimachine power system.

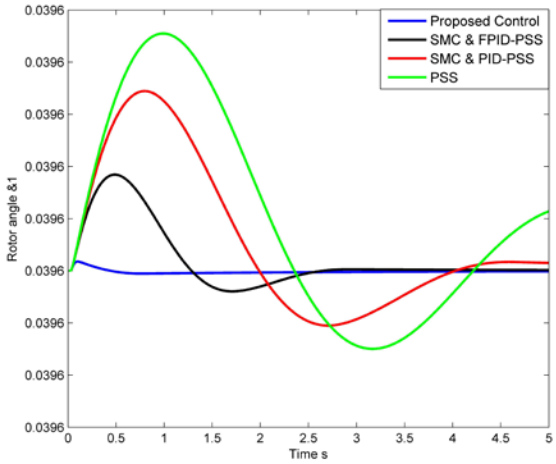

Fig.6: Rotor angle δ_1

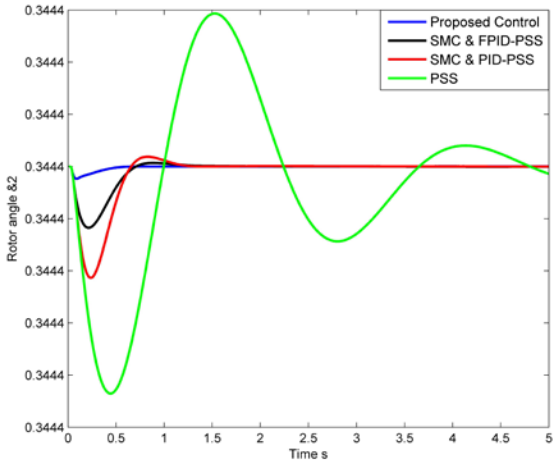

Fig.7: Rotor angle δ_2

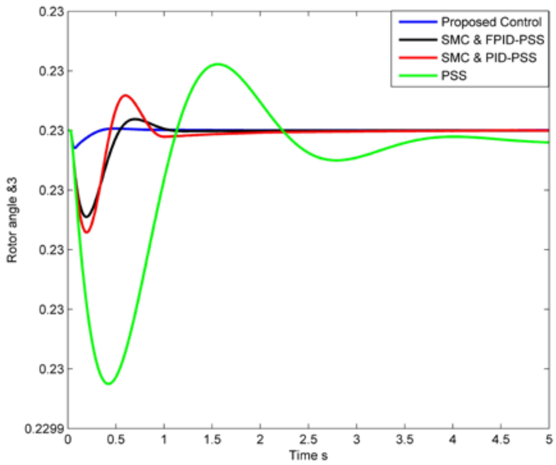

Fig.8: Rotor angle δ_3

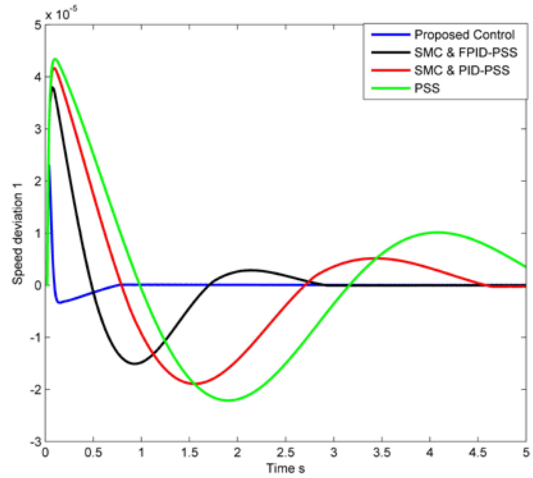

Fig.9: Speed deviation $\Delta\omega_1$

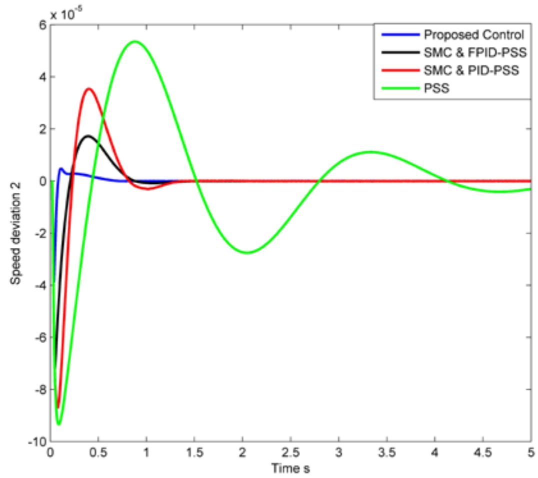

Fig.10: Speed deviation $\Delta\omega_2$

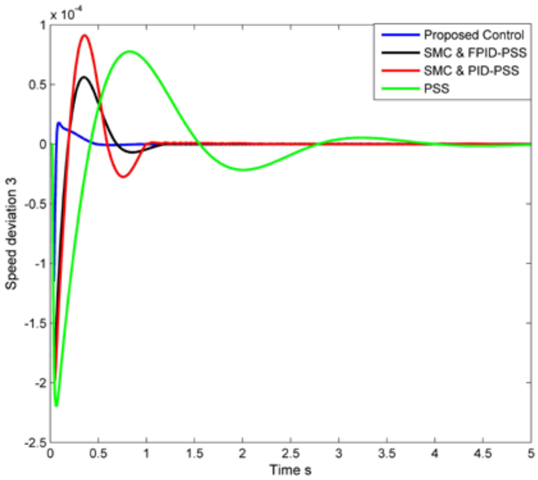

Fig.11: Speed deviation $\Delta\omega_3$

With the proposed control, the mechanical variables such as the rotor angles (δ_1, δ_2) and the speed deviation $(\Delta\omega_1, \Delta\omega_2)$ in the generators (G1 & G2) are stabilized in 0.5 and 1 second respectively; see Fig. 6-7 and Fig. 9-10. For the third generator (G3), the rotor angle δ_3 and the speed deviation $\Delta\omega_3$ are stabilized in 0.5 second; see Fig. 8 and Fig. 11. The conventional PSS controller requires more time and more oscillations before the same variables are stabilized. Implemented results in this section have demonstrated a superior performance of the proposed control in terms of eliminating the reaching phase and damping of oscillation and enhancing the stability of the system as compared with the two others controllers.

7 Conclusion

In this paper, the proposed control provides an efficient solution to eliminate the reaching phase and damp the Low frequency oscillations in the multimachine power system. A modified output tracking error is introduced in sliding mode control to reduce the control gain and to eliminate the reaching phase. The design problem of the PSS is solved and replaced by the fuzzy PID based on PSS, which enhances the stability of the power system. Also, the robustness and the performance of the proposed controller design has been proved and evaluated by the dynamic simulation results of the multimachine power system.

8 Nomenclature

δ	Rotor angle
ω	Rotor speed (pu)
$\Delta\omega$	Speed deviation
Pm	Mechanical input power
Pe	Electrical output power (pu)
M	System inertia
$E_q^{'}$	Internal voltage behind x'd (pu)
E_{fd}	Equivalent excitation voltage (pu)
$X_d^{'}$	Transient reactance of d axis (pu)
X_q	Steady state reactance of q axis (pu)
X_d	Steady state reactance of d axis (pu)
$T_{do}^{'}$	Time constant of excitation circuit (s)
T	Simulation time (s)
t_s	Settling time
T_w	Washout filter (s)
$T_1 - T_4$	Time constants of lead–lag dynamic compensator (s)
K	Gain of the Stabilizer
PSS	Power System Stabilizer
SMC	Sliding Mode Controller
PID	Proportional Integral Derivative
$FPID-PSS$	Fuzzy PID based on PSS

9 Appendix

Table 5: Nominal parameters values

Parameters	Gen1	Gen2	Gen3
H	23.64	6.4	3.01
X_d	0.146	0.8958	1.3125
X'_d	0.0608	0.7798	0.1813
D	0.3100	0.5350	0.6000
P_m	0.7157	1.6295	0.8502
T'_{do}	8.96	6.0	5.89

Table 6: Conventional PSS parameters

Parameters	K_{pss}	T_1	T_2	T_w
PSS-1	7.39	0.27	0.29	10
PSS-2	5.46	0.3	0.5	10
PSS-3	5.33	0.4	0.5	10

Table 7: Conventional PID parameters

Parameters	K_p	K_i	K_d
PID-1	60	1	5
PID-2	30	0.7	2
PID-3	27	3.1	1.3

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