Abdelghani Choucha[1,*], Lakhdar Chaib[2], Salem Arif[3]

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Robust control design of PSS for dynamic stability enhancement of power system

A Sliding Mode Controller (SMC) is adopted in this work with a Proportional Integral Derivative (PID) to achieve robust control signal and employ it instead of Power System Stabilizer (PSS). The major technique is basically focusing on the control accuracy. The main proposal is that the effective property of PID and high characteristics of SMC are combined to eliminate the chattering effect of SMC in order to generate best control signal to the excitation system. Speed deviation is chosen as sliding variables. The robust design of SMC-PID has been employed to enhance the power system stability and further to damp out strongly the system oscillations that caused by the disturbances. In order to validate the robustness of the mentioned scheme, the proposed proposition is evaluated on Single Machine Infinite Bus (SMIB) power system under different perturbations with pre-specified operating condition. For comparison, the tested power system is carried separately through different designed controllers. The simulation results have demonstrated the high performance of mentioned controller that attained best results compared to various controllers.

Keywords: PID, Power system stability, PSS, SMC, SMIB power system.

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1. Introduction

In their early years, electric power systems did not reach far from the generating station. The present power system operates adjacent to their limits as a result of the increasing use of energy and restraints on constructing new transmission lines. The power system in this situation requires a considerably a smaller amount conservative power system control and process management. Power systems are inherently nonlinear and undergo a wide range of transient conditions, that results in under damped low frequency speed as well as power oscillations that are difficult to control. Sufficient damping of oscillations is important in an interconnected power system [1].

Small signal disturbances observed on the power system are caused by many factors such as heavy power transmitted over weak tie-line, the effect of fast acting and high gain Automatic Voltage Regulators (AVRs) [1, 2]. In order to add the necessary damping to rotor oscillations, Power System Stabilizers (PSS) are used to provide oscillation damping by producing an electrical torque component in phase with the rotor speed deviations [3].

Over the past four decades, different control techniques have been developed for PSS design to enhance the performance of power system. Sliding mode control (SMC) is one of the robust techniques that applied to conquer the power system uncertainty. The advantage of SMC is that can be used in presence of unknown nonlinear function and parameter uncertainties including disturbances and operating conditions.

Many papers have proposed the method for designing the PSS using SMC such as [4]. [5,6] presented other method to design an observer via the duality between the reduced order state observer in continuous-time and the design of sliding surface in SMC. The

[*] Corresponding author: A. Choucha, Electrical Engineering Department, University of Amar Telidji, BP 37G, Laghouat 03000, Algeria, E-mail: a.choucha@lagh-univ.dz.

[2,3] Electrical Engineering Department, University of Amar Telidji, BP 37G, Laghouat 03000, Algeria.

problem is left for the discrete time case. In [7], the authors propose a new design of power system stabilizer based on fuzzy logic and output feedback sliding mode controller. Therefore, the control rules are constructed according to the concepts of output feedback sliding mode control, where the fuzzy sets, whose membership functions are identified. In [8], robust design of PSS for a Single Machine and Infinite Bus (SMIB) system has been suggested, using the duality with SMC technique based on discrete time reduced order observer. Where, the duality between discrete time reduced order observer (Reduced Order Luenberger's Observer) and discrete time sliding surface design have been established.

In recent years, designing of controller based damping has been investigated by means of various superior State feedback controls (SFC). SFC have been widely published and reported in the literature for achieving best designing of controller and for overcoming the conventional controllers [9]. Optimal control theory is suggested in [10-12] for the PSS design. Also, both Output feedback control and Pole placement methods has been proposed in [13, 14] and widely employed to attain robust control signals of PSS through actual model parameters.

Amid several computer tools, optimization and artificial intelligence have grown and utilize broadly in current researches and have been employed in the power systems area. Many metaheuristic algorithms have been reported in the literature for setting the PSS parameters. These algorithms can increase the computational efficiency, such as Genetic algorithm (GA) [15, 16], Particle Swarm Optimization (PSO) [17]. In [18], the authors have proposed a new and robust power system stabilizer (PSS), based on combination of fractional order PID controller and PSS for optimal stabilizer (FOPID-PSS), the controller parameters are obtained using a new metaheuristic optimization Bat algorithm (BA) to improve power system stability. On the other hand, artificial intelligence techniques based tuning and learning approaches have been employed to design PSS such as fuzzy logic as in [19] , artificial neural networks (ANNs) in [20], neuro-fuzzy in [21], adaptive fuzzy in [22],

The present work offers robust design of controller based on combination of sliding mode theory and PID. The stabilizer is tested through well-known Heffron–Phillip’s model. Additionally, the disadvantage of sliding mode control is overcome by adding PID to mitigate the power system oscillation after the disturbances the main role of this stabilizer is to supply better torque on the rotor part of generator and gain the proper damping of system oscillation. The mentioned controller has attained continually high effectiveness and performance in improving the stability of power system compared with SMC, PID and conventional PSS through different perturbations.

This paper is organized as follows; Section II describes the power system modeling and tested model. Section III offers statement of power system stabilizer. Short description about proposed controller theory is given in Section IV. Results and discussions of the simulation are displayed in Section V. the present work is finished by general conclusion.

2. Power System Model

In order to verify the performance of the proposed study, a single machine connected to an infinite bus power system (SMIB) was chosen. SMIB consists of a transmission line that links between synchronous generator and infinite bus. A fourth order model has been modeled the generator. While, the model used here is the Heffron-Phillips’s block diagram model to examine the small signal stability characteristics of the system. SMIB tested system is selected at this point as it is such an uncomplicated design that is particularly practical in understanding essential concepts and consequence of the stabilizer. To design the proposed controller around an operating condition, the linearization of power system should be necessary for this purpose [23]. Dynamic equations of the generator can be given as follows:

$$\dot{X} = f(X, U) \tag{1}$$

where X is the vector of the state variables and U is the vector of input variable. The state vector of n generators is given as $[\omega_i, \delta_i, E'_{qi}, E_{fdi}]^T$ and U is the PSS output signal. This model is widely used in the analysis of parameter values settings of PSS.

$$\begin{cases} \omega_i = \dfrac{(P_m - P_e - D\omega)}{M} \\ \delta_i = \omega_0(\omega - 1) \\ E'_{qi} = \dfrac{(-E_q + E_{fd})}{T'_{d0}} \\ E_{fdi} = \dfrac{-E_{fd} + K_E(V_{ref} - V_t)}{T_E} \end{cases} \tag{2}$$

δ_i is the power angle of the generator, ω_i is the speed of synchronous generator (rad/s), D_i and H_i are the inertia constant and the damping constant of the generator, P_{ei} is the active electrical power (p.u.), P_{mi} is the mechanical power where is assumed as constant value (p.u.), E'_{qi} is the quadrature-axis transient voltage (p.u.), E_{qi} is the quadrature axis electromotive force, T'_{di} is the direct-axis open-circuit transient time constant (p.u.), X_{qi} and is named as the direct-axis synchronous reactance and E'_{qi} signifies the direct-axis transient reactance of synchronous generator (p.u.), I_{di} is called the direct-axis current (p.u.), E_{fdi} represents the exciting voltage (p.u.).

In small perturbations stability studies, linearization model of power system around its operating point is often applied. The state equations of power system can be written as follows:

$$\dot{X} = AX \times BU \tag{3}$$

where A is a $4n \times 4n$ matrix and is given by $\partial f / \partial X$, while B is the input matrix with order $4n \times m$ and is given by $\partial f / \partial U$. The A and B are calculated with each operating point. The state vector X is a $4n \times 1$ and the input vector U is a $m \times 1$.

$$A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ \dfrac{-K_1}{M} & 0 & \dfrac{-K_2}{M} & 0 \\ \dfrac{-K_4}{T'_{do}} & 0 & \dfrac{-1}{K_3 T'_{do}} & \dfrac{-1}{T'_{do}} \\ \dfrac{-K_5 K_E}{T_E} & 0 & \dfrac{-K_6 K_E}{T_E} & \dfrac{-1}{T_E} \end{bmatrix} \tag{4}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & \frac{K_E}{T_E} \end{bmatrix}^T \quad (5)$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \quad (6)$$

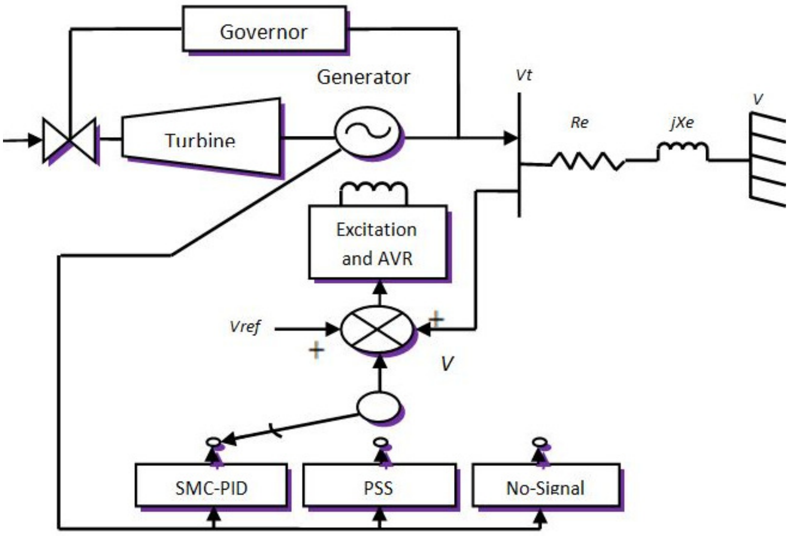

Fig. 1. Single Machine Infinite Bus (SMIB) diagram.

3. Power System Stabilizer

The PSS based damping controller is designed to generate an electrical torque in phase with the speed deviation according to the phase compensation method. In this study, the conventional lead-lag controller is used to design PSS. The structure of the PSS based damping controller is shown in Fig. 2. The rotor speed deviation is taken as the input to this controller. It has gain block, signal-washout block as well as two stages of lead-lag compensator. The phase compensation block supplies the suitable phase-lead characteristics to compensate for the phase lag between output and input signals [16]. The correct choice of the gain and time constants within their boundary limits is one of major aspect for power system stability problem. For this reason, the parameters values are optimized to keep the system from instability situation by ensuring quick and required damping.

$$V_{PSS}(s) = K \cdot \frac{sT_w}{1+sT_w} \cdot [\frac{(1+sT_1)}{(1+sT_2)} \cdot \frac{(1+sT_3)}{(1+sT_4)}] \cdot \omega(s) \quad (7)$$

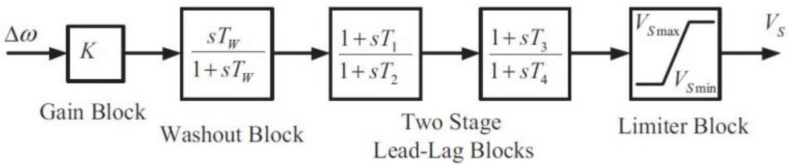

Fig. 2. Power system stabilizer model.

4. Proposed Controller

An effective design stabilizer based on the incorporation of sliding mode controller and PID is investigated in this section, the procedure was by summing the signal of SMC with the PID signal through best parameters of PID, the goal of SMC-PID controller is considered to generate a appropriate torque on the generator rotor and attain the proper damping of power system oscillation.

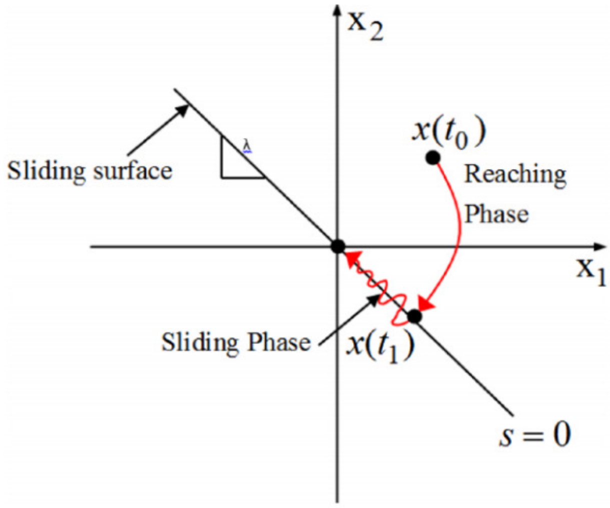

Fig. 3. Sliding model control employement.

Recently, the employment of sliding mode theory has been widely investigated as a robust approach for handling complex systems including external perturbation with uncertainties in the modeling. It is important to mention that the main step to design SMC is the concept of the sliding surface in which the desired response of control will be expected correctly. The state variable under control signal is driven toward the sliding surface.

Process of sliding mode control engages two parts, which are sliding and reaching parts. First part, the system is responsive to the disturbances and uncertainties thus the elimination thereof would yield considerable system effectiveness and enhancement.

The laws of SMC for the Eq. 3 of power system are displayed as follows;

$$u_i = -\psi_i^T X = -\sum_{j=1}^{n} \psi_{ij} x_j ; \qquad \mathrm{i} = 1,\ 2,\ldots\ldots,\ \ \mathrm{m} \tag{8}$$

where the feedback gains are presented by

$$\psi_{ij} = \begin{cases} \alpha_{ij}, & \text{if } x_i \sigma_j \rangle 0 \quad i = 1,\ldots, m \\ -\alpha_{ij}, & \text{if } x_j \sigma_i \langle 0 \quad j = 1,\ldots, n \end{cases} \tag{9}$$

and

$$\sigma_i(X) = C_i^T X = 0, \quad i = 1,\ldots, m \tag{10}$$

where C_i's are the vectors of switching which are chosen by linear optimal control theory or pole placement.

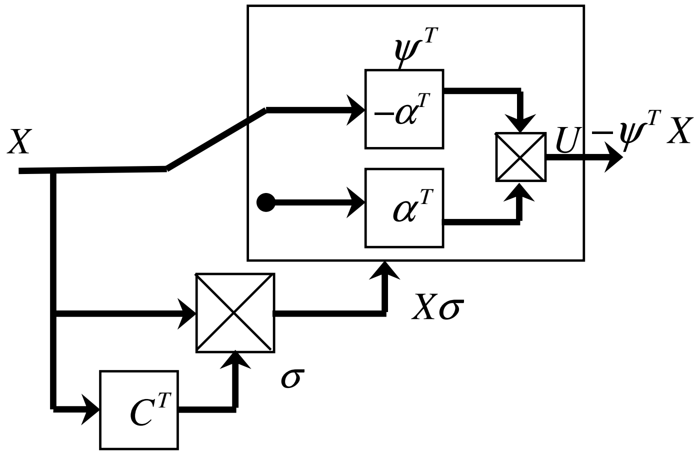

Fig. 4. Sliding mode controller (SMC) block diagram.

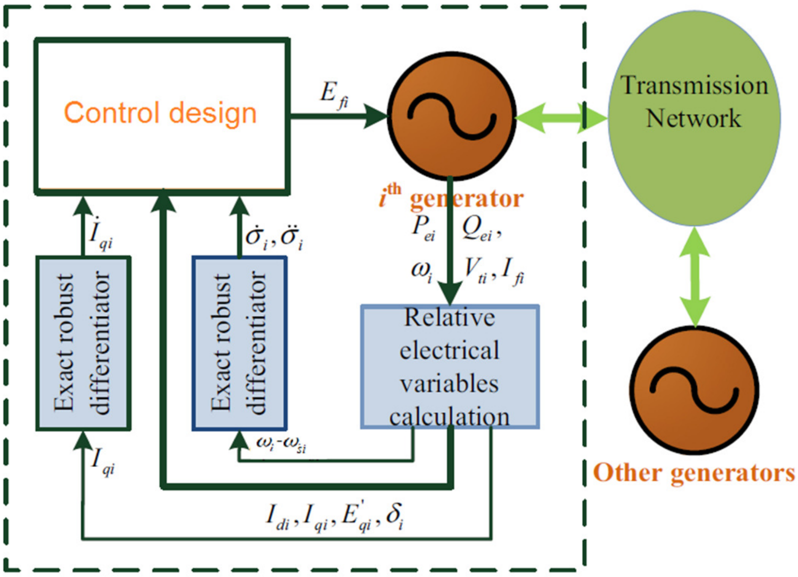

Fig. 5. Schematic plan of the proposed control system.

5. Results and Discussion

In this section, the performance of SMC and PID integration has been investigated to enhance the power system stability and achieve effective signal of control by adding supplementary damping in power system. SMC has been selected in this study as one of the most effective techniques for the mentioned field. Also, we have chosen PID controller to overcome the drawback in SMC mechanism, in which the deviations and oscillations appear in the rotor angle and speed will be obviously suppressed. The simulation is carried out in the MATLAB environment. The speed of generator in SMIB power system is sensed from the shaft and utilized as an input signal to the classical PSS while PSS output is summed to the AVR beside the reference voltage.

The proposed PSS parameters are optimally obtained using the traditional algorithm to minimize the fitness as expressed in Eq. 11 and to ensure the best comparison. As a result of the variations in system operation, power system suffers the oscillations system more considerably. For this purpose, different cases have been carried out in the simulation studies that given as follows:

- Case I: 8% step change in the reference mechanical torque;

- Case II: 10% step change in the reference mechanical torque;
- Case III: 12% step change in the reference mechanical torque.

Step change in the reference mechanical torque was sequentially augmented in order to show the effectiveness of control design under different levels of perturbation. We have chosen the changes somewhat very close to each other to manifest clearly the effects of different controllers.

In order to reveal the robustness and performance of the proposed controller, we have applied well-known performance index to measure the error of speed deviation segnal, which is Integral of Time multiplied by the Squared Error (ITSE), its form is presented as follows;

$$ITAE = \int_{0}^{tsim} t \times abs(e(t))dt \tag{11}$$

where e is the speed deviation in this study and $tsim$ is the time of simulation. The system speed deviation responses of SMIB power system under different cases are displayed in Figs. 6, 7 and 8. We can note from the results that the proposed SMC-PID exhibits much more appropriate mitigation specifications for suppressing the deviations, and quickly stabilizes the system response from the first swing under various plants and cases by providing best control signal in comparing with SMC, PID and PSS.

In addition, it is widely clear that the incorporation of SMC with PID can effectively reduce the undershoot and settling time compared to the other controllers under several conditions, which express the superiority of the proposed design. Also, the power system is effectively maintained its stability whatever the degree of perturbation in the all cases through the designed controller. It can be summarized that, the designed control strategy supplies an effective control and gives best results at the nominal loading and a wide changes in the system loading or parameters of system.

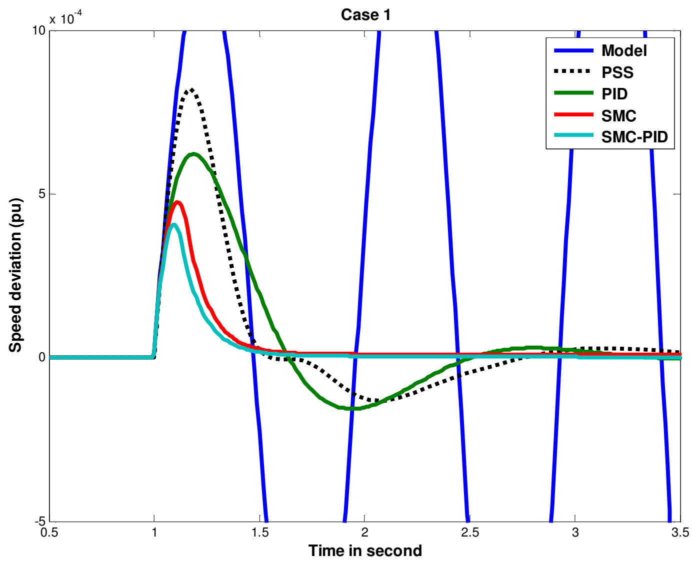

Fig. 6. Speed deviation for case 1.

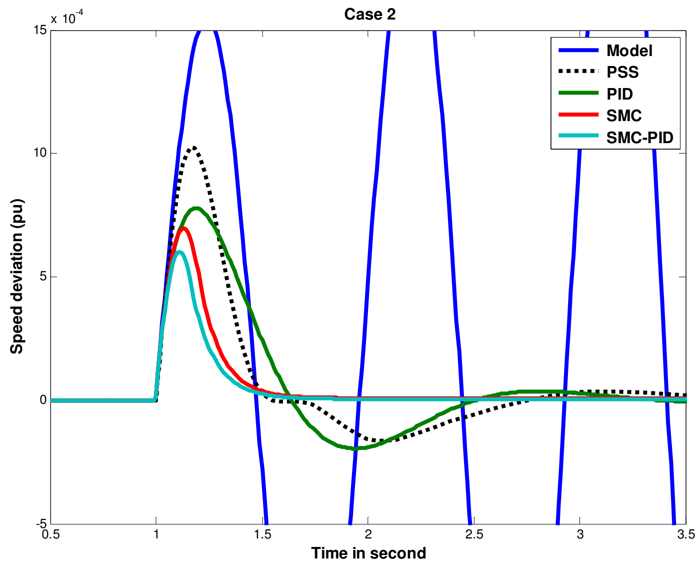

Fig. 7. Speed deviation for case 2.

Also, the power system with PSS cannot supply better damping to the system oscillations due to the limitation in its control signal. The system without controller is not able to maintain the power system in boundaries of stability as illustrated in blue line in the figures. Thus, the obtained results perceptibly demonstrate the performance and efficiency of the mentioned controller by incorporation two robust stabilizers SMC and PID for enhancing the dynamic stability in different scenarios. Deeply, It can be noticed from the obtained result that the designed controller SMC-PID obviously reveals higher performance compared to the classical PSS in enhancing the damping of system oscillations, and it wholly improve the power system stability in words of error criteria and overshoot. Furthermore, this controller is able to lead the power system to attain a stable situation very quickly to those with other controllers.

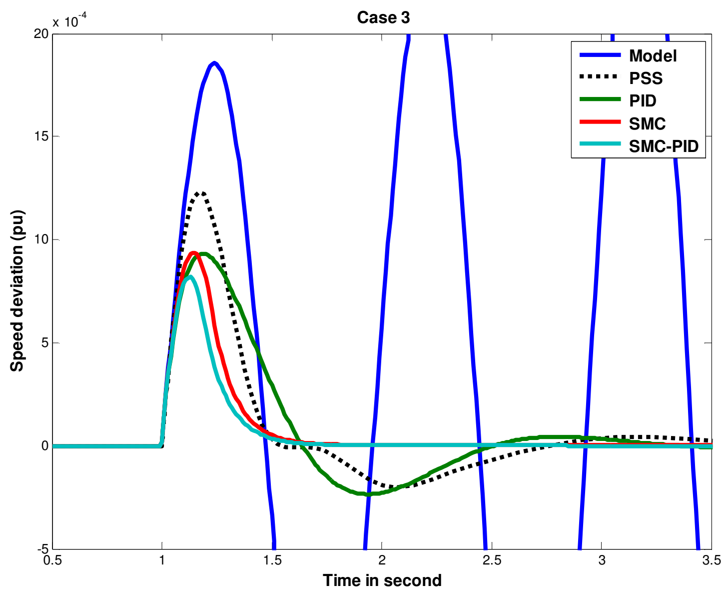

Fig. 8. Speed deviation for case 3.

Effective comparison is presented in Tables 1, 2 and 3 with different controllers and cases for superior illustration of suggested design's robustness. The results studies comparison is achieved by means of error criterion ITAE and response characteristics of speed deviations subsequent the presented disturbances.

As it is clear from these tables that the SMC-PID stabilizers attains superior damping and performance that come into view of numerical results; least value of peak, settling time and objective function. Consequently, the dominance of the suggested controller concept (SMC-PID) has been clearly proved in comparison with SMC, PSS and PID, so the overall stability of the closed-loop system has been ensured. These obtained results are caused by the fact that effective design gets compromised control signal for all considered loading conditions and perturbation.

Table 1: Objective function, Peak and settling time of speed response under case 1.

		Peak $\times 10^{-4}$	Ts	ITAE
Case 1	PSS	8.2172	3.5045	0.0018
	PID	6.2140	3.1514	2.5847×10^{-4}
	SMC	4.7508	1.7920	1.8052×10^{-4}
	SMC-PID	**4.0658**	**1.6637**	**5.7140**$\times 10^{-5}$

Table 2: Objective function, Peak and settling time of speed response under case 2.

		Peak $\times 10^{-4}$	Ts	ITAE
Case 2	PSS	10	3.5044	0.0023
	PID	7.7675	3.1514	3.2309×10^{-4}
	SMC	6.9573	1.6420	1.8394×10^{-4}
	SMC-PID	**6.0096**	**1.6089**	**8.2878**$\times 10^{-4}$

Table 3: Objective function, Peak and settling time of speed response under case 3.

		Peak $\times 10^{-4}$	Ts	ITAE
Case 3	PSS	12	3.5039	0.0027
	PID	9.3210	3.1514	3.8770×10^{-4}
	SMC	9.3785	1.6162	1.7454×10^{-4}
	SMC-PID	**8.1830**	**1.5941**	**1.1313**$\times 10^{-4}$

6. Conclusion

In this work, effective design of the control signal has been investigated based on the incorporation of sliding mode and PID controllers for improving the dynamic stability. The control signal of SMC has been enhanced using PID controller in order to achieve best command signal in the excitation system. For this purpose, the proposed controller has been tested on the SMIB power system. The simulation results obtained proved that the proposed

SMC-PID controller ensures best control signal and damps out clearly the power system oscillation under the severe perturbations and can stabilize the power system under these severe disturbances compared to other known controllers. Additionally, it guarantees adequate system damping for a wide range of system operating conditions.

We accept as true that presented control design can be effectively employed in drawing a broad part control system for mitigating the system oscillations in a multimachine power system, what is the main purpose for our future work.

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