Incorporation of sliding mode control and PID for dynamic stability enhancement of power system

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***Abstract*—A Sliding Mode Controller (SMC) is adopted in this work with a Proportional Integral Derivative (PID) to employ instead of Power System Stabilizer (PSS). The major 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. 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. The proposed proposition is evaluated on Single Machine Infinite Bus (SMIB) power system under different perturbations with pre-specified operating condition. 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.**

I. INTRODUCTION

In their early years, electric power systems did not reach far from the generating station. 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 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.

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 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.

II. POWER SYSTEM MODEL

In order to verify the performance of proposed study, a single machine connected to an infinite bus power system 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 design the proposed controller around an operating condition, the linearization of power system should be necessary for this purpose [15, 16]. 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.

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

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 $m \times 1$.

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

$$B = \begin{bmatrix} 0 & 0 & 0 & \dfrac{K_E}{T_E} \end{bmatrix}^T \tag{5}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{6}$$

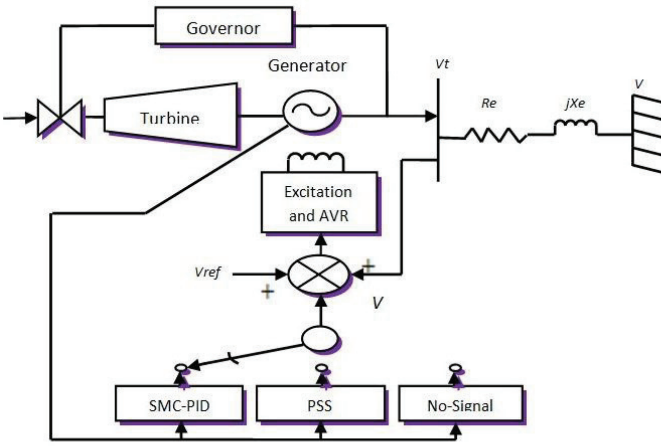

Fig. 1. Single Machine Infinite Bus (SMIB) diagram

III. 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].

$$V_{PSS}(s) = K \cdot \frac{sT_w}{1 + sT_w} \cdot [\frac{(1 + sT_1)}{(1 + sT_2)} \cdot \frac{(1 + sT_3)}{(1 + sT_4)}] \cdot \omega(s) \tag{9}$$

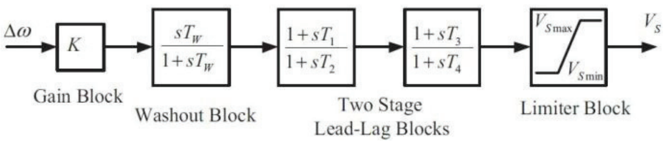

Fig. 2. Power system stabilizer model

IV. PROPOSED CONTROLLER

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.

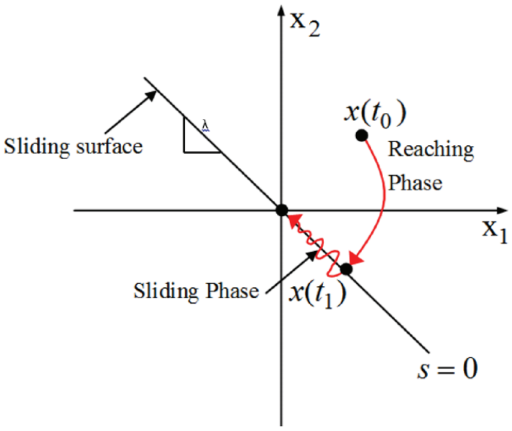

Fig. 3. Sliding model control employement.

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;

$$u_i = -\psi_i^T X = -\sum_{j=1}^{n} \psi_{ij} x_j ; \qquad \mathrm{i} = 1, 2, \ldots, \mathrm{m} \quad (10)$$

where the feedback gains are presented by

$$\psi_{ij} = \begin{cases} \alpha_{ij}, & \text{if } x_i \sigma_j \rangle 0 \quad i = 1, \ldots, m \\ -\alpha_{ij}, & \text{if } x_j \sigma_i \langle 0 \quad j = 1, \ldots, n \end{cases} \quad (11)$$

and

$$\sigma_i(X) = C_i^T X = 0, \quad i = 1, \ldots, m \quad (12)$$

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

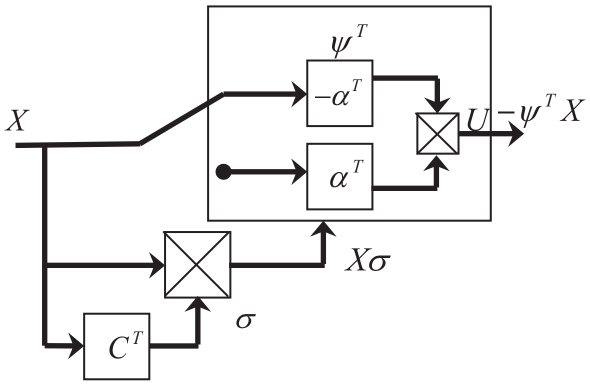

Fig. 4. Sliding mode controller (SMC) block diagram.

The operating of a PID with SMC is to produce an appropriate torque on the generator rotor involved in such a way that the phase lag between the machine electrical torque and the exciter input is strongly compensated, as given in Eq. 13. The supplementary control signal is one proportional to speed. A broadly speed input signal is considered during all the study. The placement of PID is taken beside SMC for boosting the effectiveness of control signal. The transfer function of the PID is given by:

$$U(s) = [K_p + K_i / s + K_d s] E(s) \quad (13)$$

where the parameters: K_p, K_i and K_d are the proportional, integral and differential constants.

V. 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 proposed PSS parameters are optimally obtained using the traditional algorithm to minimize the fitness as expressed in Eq. 14 and to ensure the best comparison. 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, which is Integral of Time multiplied by the Squared Error (ITSE), its form is presented as follows;

$$ITAE = \int_0^{tsim} t \times abs(e(t)) dt \quad (14)$$

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. 5, 6 and 7. 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, PSS.

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.

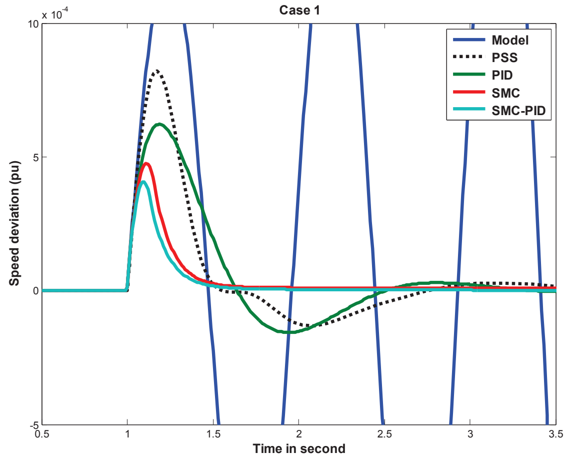

Fig. 5. Speed deviation for case 1.

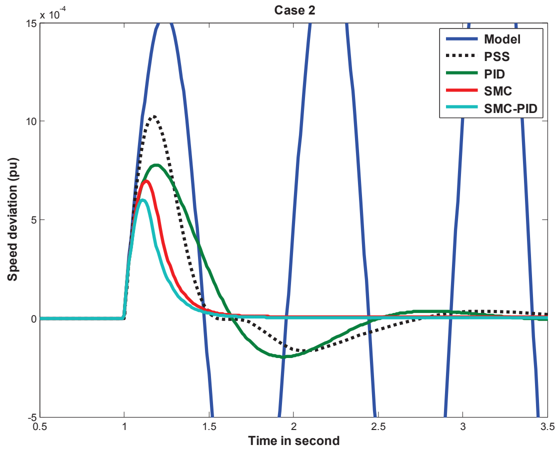

Fig. 6. Speed deviation for case 2.

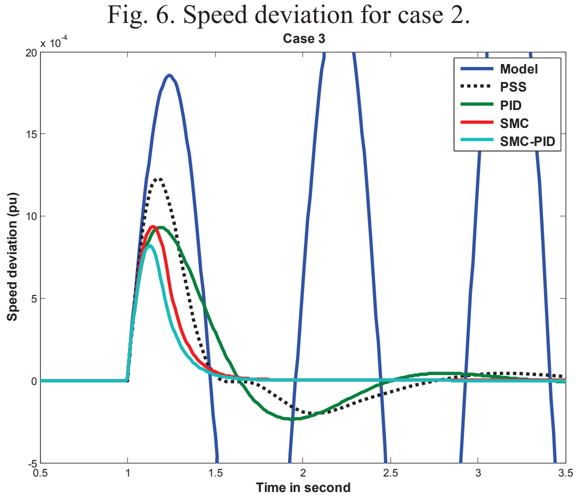

Fig. 7. Speed deviation for case 3.

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 Table 2 and 3 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.

Table 2 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**	$\mathbf{5.7140}\times10^{-5}$

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**	$\mathbf{8.2878}\times10^{-4}$

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**	$\mathbf{1.1313}\times10^{-4}$

VI. CONCLUSION

In this work, effective design of control 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 compared to other known controllers.

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