

Application of Sliding Mode Control in Single Machine Infinite Bus System (SMIB)

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Abstract: This paper presents a designing method of PSS for a single machine connected to an infinite bus, based on the technique of sliding mode control, which is robust to changes in the operating point of the system. Therefore, a range is obtained for the changes in system parameters; and a stabilizer is designed to have a good performance in this wide range. It is intended to control the increased stability and improve the dynamic response of the single machine system connected to the infinite bus in different working conditions. PSS based conventional simulation results, on sliding mode control and without PSS are compared in this paper. The results of simulations conducted on the nonlinear model of power system showed good performance of sliding mode controller. SMIB system was selected because of its simple structure, which is very useful in understanding the effects and implications of the PSS.

Key words: SMIB system, power system stabilizer (PSS), sliding mode control (SMC), chattering

INTRODUCTION

Electromechanical oscillations with small amplitude, in the frequency range 0.2 to 3 Hz, are inherent characteristics of power systems. Oscillations often appear in long periods of time, and in some cases can create restrictions on the transmission capacity of power systems. Therefore, in recent years, damping oscillations of the electric system to improve the stability of small signal in power systems has been an important issue for control engineers. Many papers have been published on this issue (DeMello, F. and C. Concordia, 1969; Larsen, E.V. and D.A. Swann, 1981; Kundur, P., 1994; Mukherjee, V. and S.P. Ghoshal, 2007; Boukarim, G.E., 2000; Sherbiny, M.K., 2003; El-Zonkoly, A.M., 2006; Kothari, M.L., 1996; Mohagheghi, S., 2007; Rao, P.S. and I. Sen, 1999; Loukianov, A.G., 2004; Yan, X.G., 2004).

Voltage regulators (VR) and excitation system with increasing torque of synchronous machine can be used to improve transient stability of the system, but it may pose a negative effect on the damping of rotor oscillations. To reduce this undesirable effect and improve the dynamic performance of the system, complementary signals are proposed to increase the damping.

One of the cost effective solution to this problem is fitting the generators with a feedback controller to inject a supplementary signal at the voltage reference input of the automatic voltage regulator to damp the oscillations. This device, known as the power system stabilizer (PSS), is now widely used in electrical industry. Regulating PSS to stabilize oscillations has been the subject of much research during the past four decades. Conventional PSS structure consists of the circuit of the dc remover and cascade lead-lag networks.

Some of the input signals are the rotor speed (slip), accelerating power, electric power and a linear combination of them, which have been widely studied, and the ways to use them in PSS design have been published in various papers.

To compensate for the phase retardation, conventional stabilizer (CPSS) makes use phase compensation method, which is caused by the excitation of generator and power system (such as torque production), and is of the same phase with the changes in speed. This is the simplest method to understand and implement, and thus is widely used in industry. For the design of PSS, it is necessary to evaluate (or regulate) several parameters for each device, such as the total dc interest, time constant of dc eliminating circuit, and constant types of the lead-lag networks. Many sequential and simultaneous methods have been reported in the literature for adjusting these parameters. In conventional method of PSS regulation, only a small number of parameters (instead of all the parameters) are regulated by a series of intuitive assumptions. Then, trial and error method is used to determine the best possible combination of these parameters, according to the performance criteria proposed. This approach gives satisfactory results on oscillation damping of local modes. However, as the PSS design is very sensitive, this result cannot be regarded as the best possible way, due to the assumptions made and the inherent nature of the design process.

The strength of PSS is an important issue. PSS must work well under changes in the operating point. In recent years, several efforts have been made in PSS design using modern control techniques, one of which is the sliding mode control. Sliding mode control theory (Slotine, J.J.E. and W. Li, 1991) has been the subject of intense study in recent years. The concept of sliding mode is to achieve the dynamics of the intended system by

restricting the system to sub-branch or sub-space of the state space. Researchers have proposed various methods to achieve this goal (Furuta, K. and Y. Pan, 2000; Hung, J.Y., 1993). Sliding mode control has advantages over other control strategies: when the system is limited to the above sub-branch (commonly called the sliding surface), the system is robust and insensitive to parameter uncertainty (Amin Rajabi, 2010). This robustness is established to examine the sliding mode control in discrete-time systems (Furuta, K., 1990; Gao, W., 1995).

Based on the simulation results, it is clear that the method proposed in this paper has produced a good response to changes in angular speed, angular position and torque for electrical changes in mechanical input.

This paper contains the following sections. The second section includes the dynamic model of SMIB system. In the third section, power system stabilizer is explained based on sliding mode control. The fourth section describes the conventional power system stabilizer (CPSS). Simulation results are presented in the fifth section. Finally, in the sixth section, a comparison is made between CPSS and PSS based on sliding mode control, and then, conclusions are presented.

Single Machine Model Connected to Infinite Bus:

Infinite bus is a source of constant frequency and voltage in amplitude and angle. A diagram of this system is shown in Figure 1.

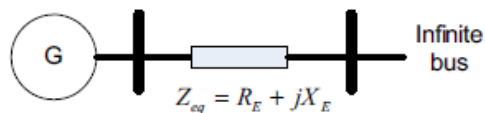


Fig. 1: A single machine connected to a large system, through a transmission line.

To analyze the stability of the small signal of the system with a synchronous machine, DeMello and Concordia have obtained a method by expanding the elements of state matrix as simple and explicit function of system parameters (DeMello, F. and C. Concordia, 1969). Figure 2 shows the block diagram modeled by Concordia, which includes the effect of excitation system.

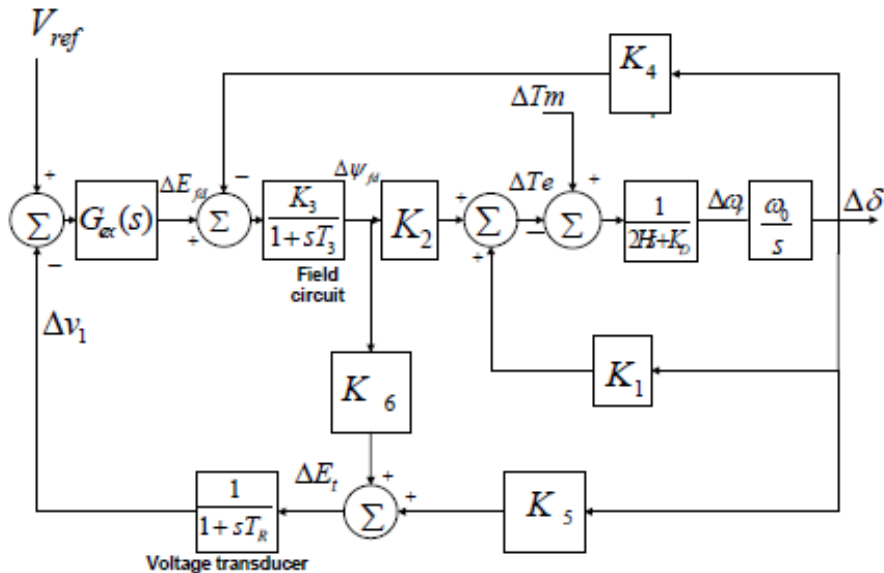


Fig. 2: Block diagram of the SMIB system with exciter and AVR.

In Figure 2, constants K_2 , K_3 and K_4 are generally positive, while coefficient K_6 is always positive; constant K_5 can be positive or negative depending on working conditions; and external network impedance is $R_E + jX_E$. The value of K_5 has an important role in effectiveness of AVR on the damping of the system's oscillations. Linear state-space model of the system, which is shown in Figure 2, is as follows:

$$\dot{x} = Ax + bu$$

Where:

$$x = [\Delta\omega \quad \Delta\delta \quad \Delta\psi_{fd} \quad \Delta v_1]^T$$

$$A = \begin{bmatrix} 0 & -\frac{K_1}{2H} & -\frac{K_2}{2H} & 0 \\ 2\pi f & 0 & 0 & 0 \\ 0 & a_{32}^* & a_{33}^{**} & a_{34}^{***} \\ 0 & \frac{K_5}{T_R} & \frac{K_6}{T_R} & -\frac{1}{T_R} \end{bmatrix}$$

$$b = \begin{bmatrix} \frac{1}{2H} & 0 & 0 & 0 \end{bmatrix}^T$$

(Relations (a_{32}^*) , (a_{33}^{**}) and (a_{34}^{***}) are given in Appendix 3.)

Power System Stabilizer Based on the Sliding Mode Control:

Power system stabilizer is used to improve the performance of synchronous generator. However, when conventional PSS is employed, it will result in poor performance under various load conditions. Therefore, using a stabilizer it is necessary to make a good performance in such conditions (here, a power system stabilizer based on sliding mode control is used).

Sliding mode control method is one of the most important non-linear control ones, whose prominent feature is lack of sensitivity to changing parameters and complete disturbance rejection and also dealing with uncertainty. Sliding mode control method has been used for over two decades to achieve robust stability in power electronics and drives. This controller brings the system from the initial state to a defined sliding surface, which has Lyapunov asymptotic stability, using the law; and then leads to equilibrium via the law of sliding. Sliding surface is a plane that the system dynamics on its both sides is such that the path of the state is guided over it, and provides a stable and desirable behavior.

Designing variable structure systems includes the following two steps:

- a. Determining the key levels, so that the intended stability and behavior can be provided.
- b. Determining the control subsystems, so that the system can go to a good sliding surface, and can provide the necessary conditions.

Consider the following dynamic single-input system:

$$\dot{X}^n = f(x) + b(x)u$$

The issue of control is that we find mode X_d so that it can follow a variable state with the specified time X_d , notwithstanding the error in $f(x)$ and $b(x)$. For the task of tracking to be done using a finite control u , the desired initial mode $X_d(0)$ must be such that:

$$X_d(0) = X(0)$$

Let the tracking error in variable x be \tilde{x} , and suppose that

$$\tilde{X} = X - X_d$$

is the tracking error vector. Furthermore, let us define a time-varying surface $S(t)$ in state space $\mathbf{R}^{(n)}$ with the scalar equation $s(X, t)$ as:

$$s(X, t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} \tilde{x}$$

Where λ is a strictly positive constant. In addition, restrictions on s can be directly moved to the restrictions of the tracking error vector X , so the scalar s is the true measure of tracking performance. As a result, following some calculations, the problem of first order to keep scalar s at zero can be obtained with the control law u of equation (1) so that outside $S(t)$:

$$\frac{1}{2} \left(\frac{d}{dt} s^2\right) \leq -\eta |s|$$

In this equation, which is called the sliding condition, η is a strictly positive constant. Now for the above system, we can choose the control law as follows:

$$u = u_{eq} - k \text{sign}(s)$$

where u_{eq} is the control estimate.

Although it is possible to determine the range of changes in k , determining the best value will be done through trial and error. If the number of controllers and inputs is high, this amount will be accompanied by a large error. Due to its nonlinear nature, the use of this controller for power system is associated with some restrictions: if the degree of system is low, the nonlinear controller can be designed using the above method. But as degree of system increases, in practice it is impossible to optimize it due to the high error in the determination of k .

A major disadvantage of this method is the problem of chattering, which has discrete signals. This problem is extended by the delays existing in the system itself. If the disturbance entering the system has a certain sign, the effect of disturbance can be removed at any time with a given control law. Sign function is a discontinuous function, which causes chattering. Discontinuity in the control causes high, frequent on/off switching in the control, leading to high energy consumption, causing noise, mechanical depreciation and excitation of non-modeled high-frequencies of system.

In most systems, chattering is an undesirable phenomenon; and a continuous function (e.g. saturation function) must be used to remove it. Accordingly, our control law is changed as follows,

$$u = u_{eq} - k \text{sat}\left(\frac{s}{\Phi}\right)$$

Where, Φ is the thickness of the boundary layer.

The most important properties that cause this method to be developed are high accuracy, fast dynamic response, good stability, ease of implementation, and good, robust stability.

Conventional Power System Stabilizer (CPSS):

Figure 3 shows a block diagram of CPSS used in this study:

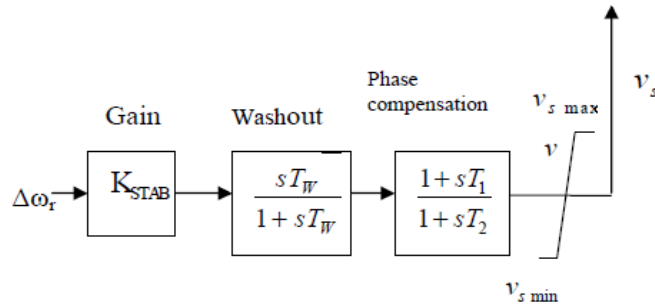


Fig. 3: Block diagram of CPSS.

The parameters of this stabilizer are given in Appendix 2.

Simulation Results:

In this paper, input PSS has been considered as the change in angular speed. Simulation results were obtained using Simulink of software MATLAB 7.6. System data and system operating point are provided in Appendix 1.

First, we consider the single machine model connected to the infinite bus with exciter and AVR for a change of 5% in mechanical input for negative and positive K_S , respectively. According to what was said, it is clear that the system does not enjoy acceptable stability at this operating point. Then, performances of two conventional controller and sliding mode controller on the sample system are discussed using the simulation.

In order to evaluate the performance of sliding mode controller on the SMIB system in Figure 1, according the dynamic model extracted, we apply simulation and control law (10), as expressed in the comments. Since the sign function is a discontinuous one, we will expect to see the chattering in the output. If we increase the simulation time, chattering becomes quite evident (Figure 4). According to what was said, we can use the control law (11) to resolve this problem, and the results of this simulation are shown in Figure 5 and 6.

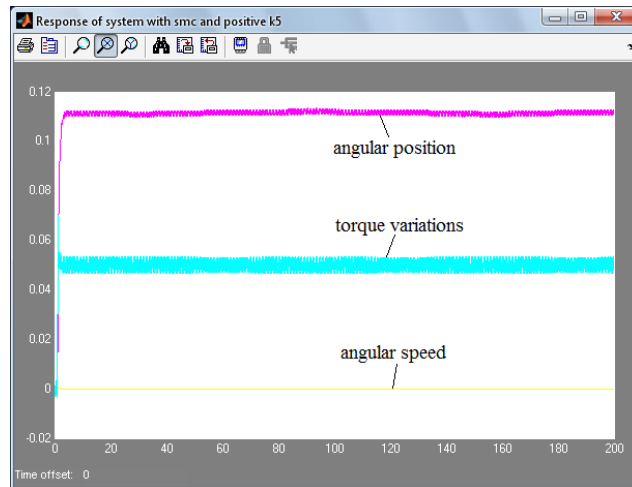


Fig. 4: System response to PSS based on the SMC for a change of 5% in mechanical input for positive K_5

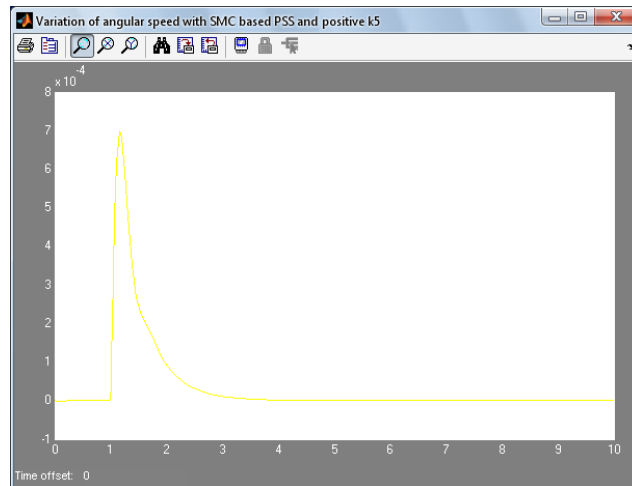


Fig. 5(a): Changes in the angular speed with the PSS based on the SMC for a change of 5% in mechanical input for positive K_5

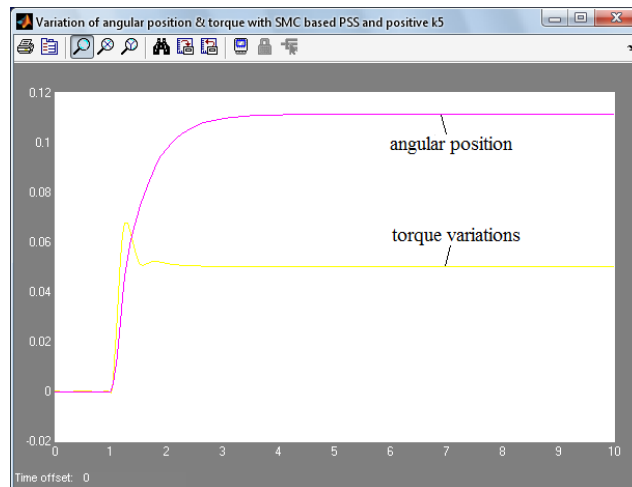


Fig. 5(b): Changes in the angular position and torque with the PSS based on the SMC for a change of 5% in mechanical input for positive K_5

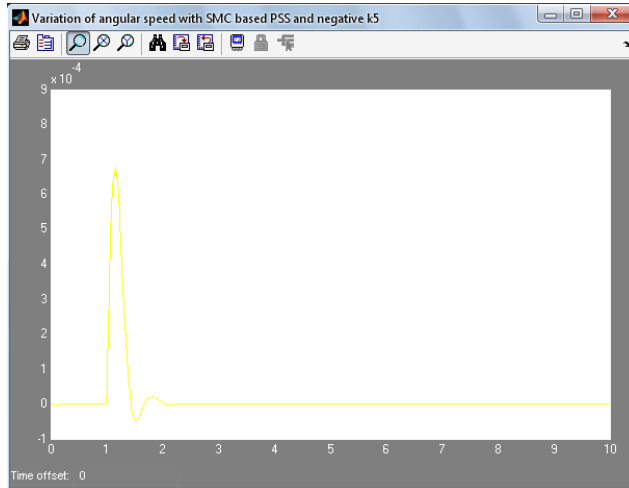


Fig. 6(a): Changes in the angular speed with the PSS based on the SMC for a change of 5% in mechanical input for negative K_5

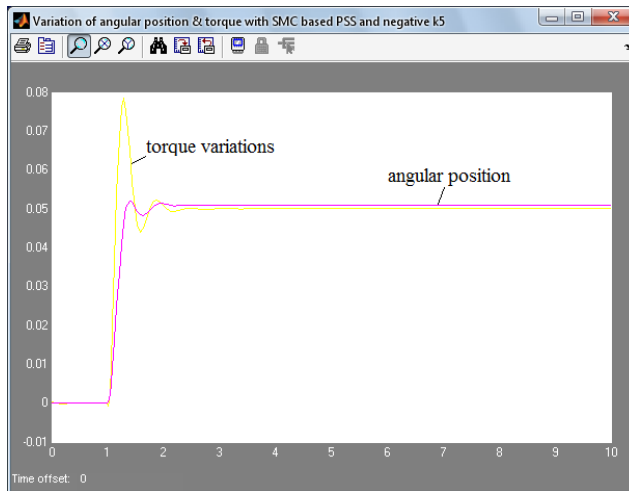


Fig. 6(b): Changes in the angular position and torque with the PSS based on the SMC for a change of 5% in mechanical input for negative K_5

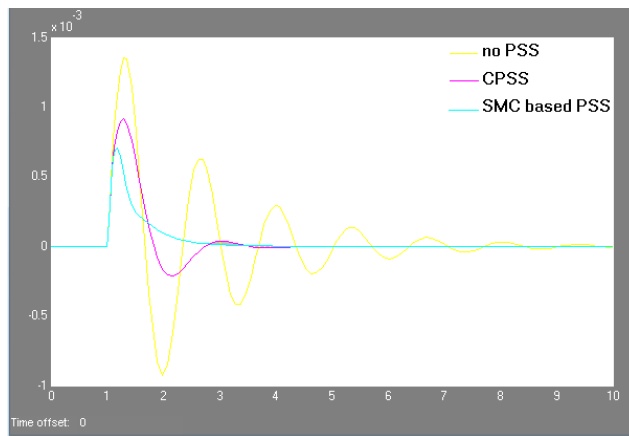


Fig. 7(a): Comparison of the angular speed for a change of 5% in mechanical input for positive K_5 , without PSS, with CPSS and PSS based on SMC.

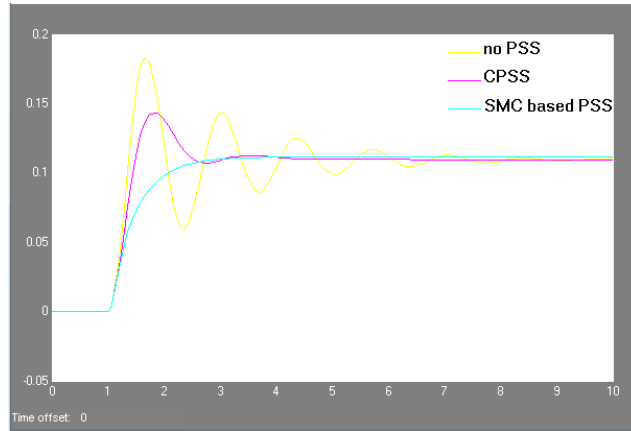


Fig. 7(b): Comparison of the angular position for a change of 5% in mechanical input for positive K_f , without PSS, with CPSS and PSS based on SMC.

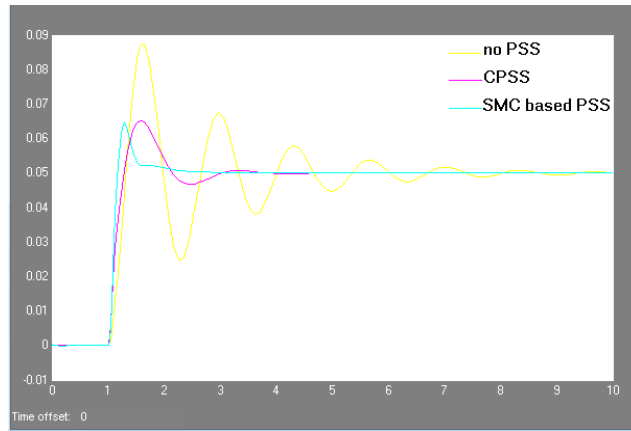


Fig. 7(c): Comparison of the electrical torque for a change of 5% in mechanical input for positive K_f , without PSS, with CPSS and PSS based on SMC.

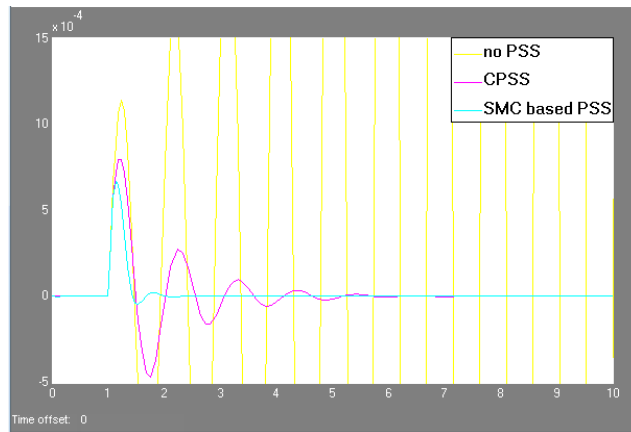


Fig. 8(a): Comparison of the angular speed for a change of 5% in mechanical input for negative K_f , without PSS, with CPSS and PSS based on SMC.

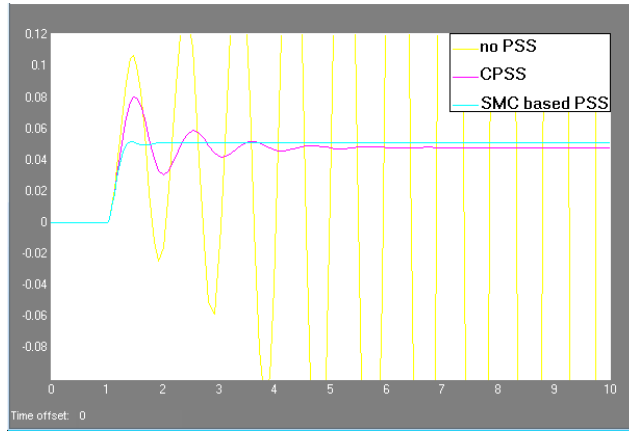


Fig. 8(b): Comparison of the angular position for a change of 5% in mechanical input for negative K_E without PSS, with CPSS and PSS based on SMC.

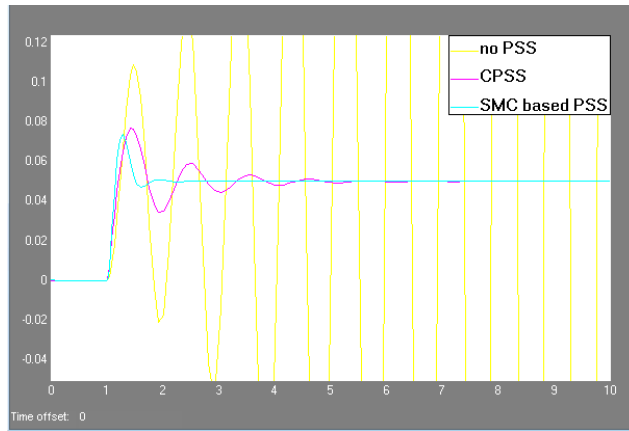


Fig. 8(c): Comparison of the electrical torque for a change of 5% in mechanical input for negative K_E without PSS, with CPSS and PSS based on SMC.

Conclusion:

PSS performance was simulated with different controllers using MATLAB Simulink. This paper suggests a new method for designing the stabilizer for SMIB using sliding mode control. In Figure 7 and 8, the performance of the system without PSS, with CPSS and PSS based on sliding mode control were compared for positive and negative K_E , respectively. The results of the simulation show that the SMC will produce the best response to speed changes, changes in the angular position and torque.

Appendix 1:

Nominal values of the system and working conditions for the above system are given in Table 1.

Table 1: Nominal values of the system and working conditions.

$P = 0.02$	$T_R = 0.02$
$Q = 0.03$	$E_{Tmag} = 1.0$
$E_f = 1.0$	$L_{adu} = 1.65$
$F = 50$	$L_{aqu} = 1.60$
$X_d = 1.81$	$R_{fd} = 0.0006$
$X_q = 1.76$	$L_{fd} = 0.153$
$X_{d1} = 0.3$	$K_{sd} = 0.8491$
$X_L = 0$	$K_{sq} = 0.8491$
$X_e = 0.65$	$K_{sd1} = 0.434$
$R_a = 0.003$	$K_{sq1} = 0.434$

$T_{do1} = 8.0$	$A_{SAT} = 0.031$
$H = 3.5$	$B_{SAT} = 6.93$
$\omega_0 = 314$	$\psi_1 = 0.8$
$K_D = 0$	

Here, the dynamical specifications of the system are expressed in expressions called the constant K.

$$K_1=0.7636, K_2=0.8644, K_3=0.3231, K_4=1.4189, K_5 = \pm 0.1463, K_6 = 0.4167$$

Appendix 2:

Table 2: Parameters of the conventional stabilizer.

Parameters	Numerical values
T_1	0.154
T_2	0.033
T_w	1.4
K_{STAB}	9.5

Appendix 3:

$$a_{32} = -\frac{\omega_0 R_{fd}}{L_{adu}} K_4$$

$$a_{33} = -\frac{\omega_0 R_{fd}}{L_{adu} K_3}$$

$$a_{34} = -\frac{\omega_0 R_{fd}}{L_{adu}} K_A$$

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