Adaptive Controller Design for SMIB System Using Sliding Mode Control

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Abstract Sliding mode control (SMC) is one of the robust control techniques with discontinuous control action. The fixed high gain in conventional SMC may lead to high-frequency oscillations in the control input known as chattering. The chattering can excite the unmodeled dynamics of the system and results in instability. Adaptive sliding mode control is one of the methods to attenuate the effect of chattering in which the gain of controller is changed based on the error dynamics. In advance SMC requires the knowledge of the time derivative of the sliding variable, which is discontinuous, so it is not measurable. This paper proposes an modified adaptive sliding mode controller based on reachability condition of sliding mode control, which can reduce the gain even in the reaching phase of the sliding mode, and also the gain is varied according to the estimated disturbance using a disturbance observer. The novelty lies to analyze the disturbances in the input dynamics and estimate the disturbance through a Leunberg observer design. The proposed control action is then applied to a single machine infinite bus, having constant voltage and frequency (SMIB) power system having DC1A exciter and power system stabilizer associated with it to evaluate the performances of the controller. At last, numerical simulation results are presented for validation purpose.

Keywords SMC · Adaptive SMC · Nonlinear control · SMIB · Disturbance observer nonlinear control · Chattering

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1 Introduction

Sliding mode controller (SMC) is having a nonlinear control strategy that can deal with the vulnerabilities in the systems. The control activity in SMC is irregular which powers the system to take after the coveted reaction. The principle favorable position of SMC is power against parameter vulnerability and results in decreased request progression. Also, SMC has a high level of adaptability in its outline decisions and the control strategy is generally simple to actualize when contrasted with other nonlinear control techniques. Such properties make SMC exceptionally reasonable for applications in nonlinear systems, and it is actualized in modern applications, for example, electrical drives, car control, process control, and so forth.

The outline system of SMC can be part into two goals. (i) Design of sliding exterior to such an extent that shut circle system is steady on this surface. (ii) Design of an intermittent controller which powers the system to achieve the sliding surface in a limited time remains there in entirely future time (positive invariance). Sliding surface is to be outlined ideally to fulfill all limitations and required particulars. The SMC has two stages. The underlying stage amid which the state direction is coordinated towards the sliding surface is called as "achieving stage," and the span in which the state direction moves towards the source along the sliding surface is called as "sliding stage." Amid the achieving stage, the shut circle system is touchy to aggravations and thus the most critical assignment is to outline a controller that drives the system directions to the sliding surface in a limited time and keep up it at first glance even within the sight of vulnerabilities and unsettling influences. Henceforth, SMC is uncaring to coordinated vulnerabilities and aggravations on the sliding surface and the shut circle system takes after a lessened request flow. If there should arise an occurrence of ordinary SMC, the pickup of irregular control activity is settled and the execution of traditional SMC continuously is influenced by the marvel known as "prattling" which is because of the high recurrence broken control activity close to the sliding surface. Prattling is unfortunate since it can energize unmodeled system elements and prompt precariousness of the system. Numerous techniques have been created to diminish prattling in SMC which incorporate limit layer control and higher request sliding mode control (HOSM). Sliding mode controller design objective generally lies in twofold (i) To select a sliding surface (ii) The trajectories of the closed-loop controller will follow the reaching phase of controller in finite time and be there is discussed [1–3]. Most of time during the controller design the value of controller gain is high to overcome effect of disturbances, but by doing this we have to compromise for chattering; again, high gain chattering is added when the closed-loop control trajectories have to reach the reaching phase $S(x) = 0$. Due to high-frequency dynamics and excitement because of chattering, the control input should be free from chattering as discussed in [4]. The problem of finite-time-based constrained stabilization with uncertainties is discussed in [8]. To avoid high-frequency chattering previously researcher has followed various methods such as designing controller based on boundary layer [5], appropriate switching function choosing [6, 7], higher-order sliding mode control (HOSMC) [8] and adaptive SMC design with adjustable

controller gain [9, 10]. Increasing the gain in a small range around the switching region is provided in [10]. The sliding mode controller application for closed-loop tracking control of a DC machine along with improved chattering performances is discussed in [10].

In this work, we have proposed an adaptive SMC and gain of the SMC is adapted according to error minimization of estimated disturbance, with the help of linear observer design. The novel technique is next applied to a SMIB power system having nonlinear exciter and also having power system stabilizer. The rest of the paper is organized as follows: Sect. 2 represents the design of existing adaptive sliding mode controller, and Sect. 3 deals with observer design for input disturbances in the controller. To validate the proposed controller, simulation results are explained in Sect. 5 that followed by a conclusion in Sect. 6.

2 Existing Adaptive SMC

A noteworthy disadvantage of customary SMC is settled pickup which is gotten through the bound of disturbances. This may bring about overestimation and prompts chattering and may lead to chattering. The chattering could energize the unmodeled flow of the system and may prompt unstability. The chattering can be diminished by fluctuating the pickup of SMC in light of the immediate disturbances. In the following area, diverse kinds of adaptive sliding mode controller of this specific nature are talked about.

2.1 Design of Adaptive SMC

Consider a nonlinear signal input of any system

$$\dot{x} = f(x) + g(x) * u + d \tag{1}$$

where x is the state vector, u is the control input, and d is the external disturbance. The functions $f(x)$ and $g(x)$ are the control inputs which are drifted, so the exact value is not known. Equation (1) can be written as

$$\dot{x} = (f(x) + \partial x) + (g(x) + \partial x) * u + d \tag{2}$$

where in $f(x)$ and $g(x)$ are nominal parts of the system and the variant in $f(x)$ and $g(x)$ are parameter uncertainties.

Let us consider, there exist a sliding Surface-

$$S(x) = R^n \to R \tag{3}$$

The sliding function described in Eq. (3) in such a manner that the system described in (1) is stable in the switching manifold. The objective of the controller design is to determine a control input such that to reach the switching manifold and stay there for infinite time, which can be achieved by the help of Lyapunov condition such as

$$S\dot{S} = -\beta(t)|s| \tag{4}$$

This equation will provide negative energy function, and absolute stability is achieved according to Lyapunov theory.

Let us define a control input as

$$u \equiv u_0 + u_s \tag{5}$$

$$u_0 = -\left[\frac{\partial S}{\partial x}(g_0(x))^{-1}\right]\frac{\partial S}{\partial x}(f_0(x)) \tag{6}$$

$$u_s = -\left[\frac{\partial S}{\partial x}(g_0(x))^{-1}\right]K\operatorname{sign}(s(x)) \tag{7}$$

Generally, in case of SMC design, the gain of the controller is adjusted in such a way that it may compromise either with robustness or with chattering. So the best method is to adopt the value of K to avoid either underestimation or overestimation.

3 Observer Design for Disturbance Estimation

Estimating the unknown disturbances in the control input is quite challenging task. Designing a Leunberg observer for estimation purpose will really help the purpose. Estimating the unknown disturbance d, which itself a function of state variable, control input and disturbance in such a fashion that controller gain K will be adjusted itself to satisfy Lyapunov condition.

Consider the dynamics of sliding function such as

$$S = d + u_s \tag{9}$$

Again let the observer designed have dynamics such as

$$\dot{p} = l(l\dot{S} - p + u_s) \tag{10}$$

$$\tilde{d} = lS - p \tag{11}$$

$$d = l(d + u_s) - l(S - p + u_s) \tag{12}$$

$$d = ld - l\tilde{d} = -le \tag{13}$$

than the dynamics of error will be

$$\dot{e} = le - l\tilde{d} \tag{14}$$

By choosing the higher value of observer gain 'l', the error dynamics will reduce to '0', iff and only if the estimated error magnitude reduces to '0'.

4 Adaptive SMC for SMIB System

A SMIB system having nonlinear exciter can be modeled as follows with the help of exact linearization design approach

$$\dot{\delta} = \omega - \omega_0 \tag{15}$$

$$\dot{\omega} = \frac{\omega_0}{H} P_H + \frac{\omega_0}{H} P_{ML0} - \frac{D}{H}(\omega - \omega_0) - \frac{\omega_0}{H} \frac{E_q V_f}{\sum X'_d} \sin\delta \tag{16}$$

$$\dot{E}'_q = \frac{\sum X_d}{X'_d \sum T_{D0}} E'_q + \frac{1}{T_{D0}} \frac{X_d - X'_d}{\sum X'_d} V_f \cos\delta + \frac{1}{T_{D0}} V_f + K_{\text{Stab}} \frac{d\Delta\omega_r}{dt} \frac{1}{T_D} \tag{17}$$

$$V_f = E_q + \frac{dE_q}{dt} = u \tag{18}$$

where the angle between EMF and terminal voltage of the synchronous generator, the rotor speed of the generator, and voltage behind the transient reactance are δ, ω, ω_0, Eq, respectively. P_{ML0} and P_H are the turbine lower limit and higher limit, and stabilization constant is represented by K_{Stab}. The value of stabilization constant should be wisely declared to avoid high-frequency attenuation.

Here, in this paper, we have considered a power system stabilizer (PSS) to add damping to generator rotor oscillation for excitation voltage control. The state space modeling of the controller is shown below

$$[\dot{x}] = \begin{bmatrix} E_q \delta\omega \end{bmatrix}^T \tag{19}$$

$$\dot{x} = f(x) + g(x) * u + d \tag{20}$$

$$f(x) = \begin{bmatrix} \frac{1}{T_{D0}} E'_q + \frac{1}{T_{D0}} \frac{X_d - X'_d}{\sum X'_d} V_f \cos\delta + K_{\text{Stab}} \Delta\omega_r \\ \frac{\omega_0}{H} P_{ML0} - \frac{D}{H}(\omega - \omega_0) + \frac{E_q V_f}{\sum X'_d} \sin\delta \\ \omega - \omega_0 \end{bmatrix} \tag{21}$$

$$[g(x)] = \begin{bmatrix} \frac{1}{T_{D0}} \\ 0 \\ 0 \end{bmatrix} \tag{22}$$

where H represents inertia constant of the synchronous generator, D specifies damping coefficient associated with the machine, X'_d is the direct axis transient reactance, and X_s specifies for steady-state reactance.

The equivalent state space modeling of the SMIB system has done with assuming the state of the system as represented in Eq. 19.

Time constant of the SMIB system has very significant role in the modeling process; high value of time constant will have less settling time but with settled at any unwanted value.

$$\dot{x}_1 = f(x_1) + g(x_1) * u + \frac{K_{\text{Stab}}}{T_D} \frac{\Delta\omega_r}{T_D} \tag{23}$$

$$\dot{x}_2 = x_3 \tag{24}$$

$$\dot{x}_3 = f(x_2) + g(x_2) * u - \frac{d}{dt} \frac{D}{H} x_2 \tag{25}$$

The switching function and sliding function have been taken according to the significance as discussed previously.

$$S = C_1 * x_1 + C_2 * x_2 + C_3 * x_3 \tag{26}$$

$$u_{\text{switching}} = K_t \text{sign}(S) \tag{27}$$

The uncertainty in the control input can be balanced by regulating the value of K_t, which adapts itself by the error dynamics.

5 Numerical Results

This section represents the validation results of designed adaptive SMC for SMIB system having a nonlinear exciter and a power system stabilizer associated with it. The following data have been taken for simulation purpose $D = 3.1 \sin t + 3t + 5$ pu, $\Delta\omega_r = t + 0.98$ pu, and other data are in Table 1.

Table 1 Numerical data for validation

H	T_{D0}	X_d	$\sum X'_d$	ω_0	E_{q0}	C_1	C_2	C_3
10	5 s	0.962 pu	0.344 pu	314 rad/s	1.405 pu	10	1	0.5
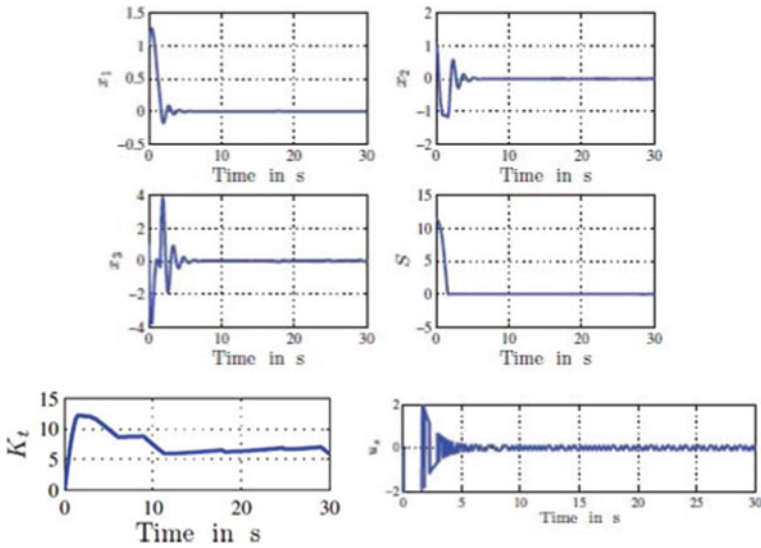
The simulation results of all state variables along with controller gain are shown above. The controller gain is adapted itself by minimizing the error in dynamics, which can be possible by observer gain analysis.

From the above simulation results, it is conforming that all dynamics of state variable are approaching to zero as time progress and the controller gain 'K' adapted accordingly to maintain the reachability condition and the controller input should be within the manifold. In an observer-based controller design, change in state variable amplitude will be less and hence less chattering.

6 Conclusion

This paper discusses the estimation of the disturbances and also tuning of the value of controller gain 'K' such that switching manifold is reached in finite time and stays there for longer. The same technique is applied to a SMIB power system with non-linear DC1A exciter modeling along with (PSS), and the dynamics of state variable are approaching to zero with lesser chattering as per the specified objective. The same techniques can be applicable to multimachine system angle stability analysis and voltage stability analysis for power system.

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