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SLIDING MODE BASED CONTROL AND OBSERVER DESIGN FOR SERIES DC MOTOR VELOCITY REGULATION

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Abstract. *This paper presents methods for designing sliding mode based control and observer using feedback linearization in order to obtain a linearized model of the system. Control and observer have been designed for a series DC motor, nonlinear system where the feedback linearization method is applied. A small number of studies examines the case when the armature current is estimated, and the sensor for the rotor velocity is present. The motivation for implementing feedback regulation based on estimated variables in practical applications lies primarily in reducing system costs. It is assumed that the angular velocity of the series DC motor can be measured, and sliding mode observer is used to estimate the armature current. The sliding mode control based on the so-called power rate reaching law is used. Its main characteristic is minimizing chattering, both in the control signal and the switching function. Due to the singularity at the start of the experiment when the armature current is zero, its value is constrained. It is experimentally shown that the estimated value converges to the measured output signal value of the series DC motor. The same holds even in the presence of white noise with a standard deviation of 1.0, although the effects are noticeable under these conditions. The presented simulation results are obtained using the Matlab/Simulink environment and are provided at the end of the paper.*

Key words: *series DC motor, sliding mode controller, sliding mode observer, Lie derivative, feedback linearization.*

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1. INTRODUCTION

In cases where certain state coordinates of a system cannot be measured, it is necessary to estimate them in order to provide effective control and monitoring. These state coordinates represent a mathematical representation of the system model that we aim to control or monitor. For this purpose, it is necessary to design an observer that will provide estimated values of the required state coordinates of the system. The input signals to the observer block typically represent the input signals of the system itself and the difference between the measured state coordinates of the original system and the corresponding outputs from the observer. One of the earliest approaches for observer design is the Luenberger method, which was first applied to linear systems [1, 2]. It has been shown that the state coordinates of linear systems can be estimated based on the system's outputs and inputs and that the outputs obtained from the observer can be used instead of the original system states to design the feedback control for both linear and nonlinear systems. The extended Luenberger observer for the problem of measuring the rotor position was presented in [3]. More complex mathematical structures were used for state estimators later. For plants where high disturbance is present, authors in [4] proposed a nonlinear adaptive Kalman filter. The Kalman and extended Kalman filter was also used in [5] for estimating the armature current of a DC motor. A fuzzy based Takagi-Sugeno state estimator was used in [6]. A general state estimator, for any DC motor configuration, is shown in [7] where the passivity theory is used for estimator design.

Another family of methods for designing observers is based on the sliding mode [8]. The robustness, which is one of the main characteristics of the sliding mode control (SMC), is also very useful in this case, especially when there are uncertainties or errors in the system model. An approach for designing observers for a certain class of nonlinear systems is presented in [9]. A sliding mode observer (SMO), which uses the observer error and switching expression, allows the estimated output error of the system to converge to zero in finite time. This also enables the state coordinates of the observer to asymptotically converge to the system's state variables [10]. In [11], an observer is designed based on the equivalent control method, which allows for the estimation of the state of a nonlinear system without a nonlinear state transformation. A second-order sliding mode disturbance observer is proposed in [12] to estimate and compensate for the aperiodic disturbances. The improved SMO-based repetitive control has been designed in [13] to improve the signal tracking of the system in the presence of input and state time delays and input disturbances. To estimate and compensate for exogenous disturbances and nonlinearities, an integral sliding mode disturbance observer based preview repetitive control law is presented in [14]. The chattering phenomenon in sliding mode is a known disadvantage of this control technique. There are many approaches for control and observer design which deal with suppressing the chattering. In [15], an adaptive sliding mode observer-based sensorless control for a surface-mounted permanent-magnet synchronous machine is presented. This approach is used to suppress the chattering problem of sliding mode observers. A model-free finite-time terminal SMC algorithm for uncertain robot systems is applied in [16]. A nonsingular fast terminal sliding surface is determined to achieve a faster convergence rate. In this paper, the authors have used a boundary layer technique to reduce the chattering phenomenon. Nevertheless, not many studies examine the scenario in which the current is estimated rather than directly measured. The motivation for the practical realization for feedback regulation based on estimated variables is related to the cost reduction especially in high-frequency drive applications that require high-bandwidth current sensors and high-resolution A/D converters [17]. In [18], the authors presented methods for the design of Luenberger, extended Kalman and extended sliding mode observer where the rotor velocity is measured and the current is treated as an estimated variable.

In order to obtain a good approximation of the real system, an appropriate model is needed. Although the exact mathematical model cannot be easily determined, there are a lot of techniques for obtaining a linearized representation of a nonlinear system. In the past decades, feedback linearization has been the technique that was often used for nonlinear transformation along with the use of linear control laws [19-22]. It is a very useful nonlinear strategy that operates by canceling nonlinearities. This method has been successfully used within a number of control applications such as for DC/DC converters [23, 24], microgrids [25], power systems [26, 27] or robot manipulators [28].

Unlike previous approaches, this study presents a novel combination of SMC and SMO with the feedback linearization method. The controller and observer are designed and applied to a nonlinear series DC motor system. Feedback linearization and estimated state values along with SMC are applied to obtain an appropriate linear model from the initial nonlinear model of the series DC motor. The paper is organized as follows: Sections 2 and 3 provide the theoretical basis for designing SMOs and SMC, respectively. The methods for designing observers and SMC based on the so-called power rate reaching law applied to the series DC motor model are discussed in Section 4. Simulation results are presented in Section 5, and the conclusion and comments regarding the obtained results are given in Section 6.

2. SLIDING MODE BASED OBSERVER DESIGN

We will consider the following nonlinear system:

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

$$y = h(x) \,, \tag{2}$$

where x represents the system state vector, y is the system output, $f(x)$ and $g(x)$ are nonlinear functions of the state vector, u is the control signal, and $h(x)$ is a scalar function. To verify whether the system can be linearized using the feedback linearization method, we will use the Lie derivative operations [9, 29]. A nonlinear system can be linearized using the feedback linearization if it satisfies the conditions that the relative degree of the system is equal to the order of the system [14]:

$$L_g L_f^{i-1} h(x) = 0, i = 1, 2, \ldots, \rho - 1 \,, \tag{3}$$

$$L_g L_f^{\rho-1} h(x) \neq 0 \,. \tag{4}$$

If conditions (3) and (4) are satisfied, the following coordinate transformation of the system is introduced:

$$z = H(x) = \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_n \end{bmatrix} = \begin{bmatrix} h(x) \\ L_f h(x) \\ \vdots \\ L_f^{n-1} h(x) \end{bmatrix} . \tag{5}$$

Using the transformation (5), the nonlinear system (1) can be linearized, resulting in a system in the following form:

$$
\begin{aligned}
\dot{z}_1 &= z_2, \\
&\vdots \\
\dot{z}_{n-1} &= z_n, \\
\dot{z}_n &= L_f^n h(x) + L_g L_f^{n-1} h(x) u.
\end{aligned} \tag{6}
$$

The state feedback control u is defined as:

$$
u = \frac{1}{L_g L_f^{n-1} h(x)} \left[\nu - L_f^n h(x) \right], \tag{7}
$$

which transforms (6) into

$$
\begin{aligned}
\dot{z}_1 &= z_2, \\
&\vdots \\
\dot{z}_{n-1} &= z_n, \\
\dot{z}_n &= \nu.
\end{aligned} \tag{8}
$$

This is feasible only when all state variables can be measured. However, in real situations, this is often not possible. In such cases, it is necessary to design a state observer. To obtain the estimated values of the transformation $H(x)$, it is necessary to calculate the estimated values of the functions $f(x)$ and $g(x)$, i.e., $\hat{f}(x)$ and $\hat{g}(x)$, respectively. The observer for the transformed system is proposed in the following form:

$$
\begin{aligned}
\dot{\hat{z}}_i &= \hat{z}_{i+1} - \alpha_1 \tilde{z}_1 - K_1 \operatorname{sgn}(\tilde{z}_1), \\
&\vdots \\
\dot{\hat{z}}_n &= -\alpha_n \tilde{z}_1 - K_1 \operatorname{sgn}(\tilde{z}_1) + L_f^n h(\hat{x}) + L_g L_f^{n-1} h(\hat{x}) u,
\end{aligned} \tag{9}
$$

where $\tilde{z}_1 = \hat{z}_1 - z_1$.

The observer error is now given by $\tilde{z} = \hat{H}(x) - H(x)$. The observer error dynamics is:

$$
\begin{aligned}
\dot{\tilde{z}}_i &= \tilde{z}_{i+1} - \alpha_1 \tilde{z}_1 - K_1 \operatorname{sgn}(\tilde{z}_1), \\
&\vdots \\
\dot{\tilde{z}}_n &= -\alpha_n \tilde{z}_1 - K_1 \operatorname{sgn}(\tilde{z}_1) + L_f^n h(\hat{x}) + L_g L_f^{n-1} h(\hat{x}) - L_f^n h(x) - L_g L_f^{n-1} h(x).
\end{aligned} \tag{10}
$$

To achieve the stability of the error dynamics, the parameters α_i and K_i, $i = 1,\ldots,n$ must be calculated. If we use (7) with the estimated values of the transformed system and substitute into (9), the observer takes the following form:

$$
\begin{aligned}
\dot{\hat{z}}_i &= \hat{z}_{i+1} - \alpha_1 \tilde{z}_1 - K_1 \operatorname{sgn}(\tilde{z}_1), \\
&\vdots \\
\dot{\hat{z}}_n &= -\alpha_n \tilde{z}_1 - K_1 \operatorname{sgn}(\tilde{z}_1) + L_f^n h(\hat{x}) + L_g L_f^{n-1} h(\hat{x}).
\end{aligned} \tag{11}
$$

3. Sliding Mode Control Design

Consider a system of the form:

$$\dot{x}_1 = x_2,$$
$$\dot{x}_2 = f(x) + g(x)u, \tag{12}$$

where $f(x)$ and $g(x)$ are unknown nonlinear functions and $g(x) \geq g(0) > 0$.
The design of the controller consists of two steps. The first step is establishing the motion where the system trajectories will move towards the sliding surface $s = 0$ and reach it in finite time; the second step is establishing the motion of the system trajectories along the sliding surface. The first step is called the reaching phase, and the second step is the sliding phase. If we choose the switching function as:

$$s = cx_1 + x_2, \tag{13}$$

the sliding surface will be defined as:

$$s = 0, \tag{14}$$

The motion of the system trajectory is then defined by:

$$\dot{x}_1 = x_2 = -cx_1, \tag{15}$$

To ensure the stability of the system, a Lyapunov function of the form:

$$V = \frac{1}{2}s^2, \tag{16}$$

is used. The derivative of the function V is

$$\dot{V} = s\dot{s} = s\left[cx_2 + f(x)\right] + g(x)su, \tag{17}$$

Assume that the derivative of the switching function satisfies the following inequality:

$$\left|\frac{cx_2 + f(x)}{g(x)}\right| < \rho(x), \quad \forall x \in R^2, \tag{18}$$

for some known functions $\rho(x)$. From (17) and (18), the following inequality is obtained:

$$\dot{V} = s\dot{s} \leq g(x)|s|\rho(x) + g(x)su. \tag{19}$$

If the control u in (19) is defined as:

$$u = -\beta(x)\,\mathrm{sgn}(x), \quad \beta(x) \geq \rho(x) + \beta_0 > 0, \tag{20}$$

where:

$$\mathrm{sgn}(s) = \begin{cases} 1, & s > 0, \\ 0, & s = 0, \\ -1, & s < 0, \end{cases}$$

and substituting (20) into (19), the conditions for the system trajectory to reach the sliding surface $s = 0$ and stay on it thereafter are satisfied if:

$$\dot{V} \leq -g_0\beta_0|s|. \tag{21}$$

4. Series DC Motor Sliding Mode Control and Observer Design

In this section, the designed sliding mode based observer and controller will be applied to series DC motor.

4.1. Sliding mode observer design

A series DC motor with the following mathematical model is considered [19]:

$$\begin{aligned} J\frac{\mathrm{d}\omega}{\mathrm{d}t} &= K_m L_f i^2 - D\omega - \tau_L, \\ L\frac{\mathrm{d}i}{\mathrm{d}t} &= -Ri - K_m L_f i\omega + \frac{1}{L}u. \end{aligned} \tag{22}$$

By choosing $x_1 = \omega$ and $x_2 = i$, the following system of equations is obtained:

$$\begin{aligned} \dot{x}_1 &= a_4 x_2^2 + a_5 x_1 + a_6, \\ \dot{x}_2 &= a_1 x_2 + a_2 x_1 x_2 + a_3 u, \end{aligned} \tag{23}$$

where:

$$\begin{aligned} &a_1 = -R/L, a_2 = -K_m L_f/L,\ a_3 = 1/L, \\ &a_4 = K_m L_f/J,\ a_5 = -D/J, a_6 = -\tau_L/J = const. \end{aligned}$$

The system (23) can now be represented in the form of (1) where:

$$f(x) = \begin{bmatrix} a_4 x_2^2 + a_5 x_1 + a_6 \\ a_1 x_2 + a_2 x_1 x_2 \end{bmatrix}, \tag{24}$$

$$g(x) = \begin{bmatrix} 0 \\ a_3 \end{bmatrix}. \tag{25}$$

A coordinate transformation transforms the previous system into:

$$\begin{aligned} z_1 &= h(x) = x_1, \\ z_2 &= L_f h(x) = a_4 x_2^2 + a_5 x_1 + a_6, \end{aligned} \tag{26}$$

thus, the system (23) is now given in the form:

$$\begin{aligned} \dot{z}_1 &= z_2, \\ \dot{z}_2 &= L_f^2 h(x) + L_g L_f h(x) u. \end{aligned} \tag{27}$$

State feedback control is chosen as:

$$u = \frac{1}{L_g L_f h(x)}[v - L_f^2 h(x)], \tag{28}$$

which results in a controllable linear system:

$$\begin{aligned} \dot{z}_1 &= z_2, \\ \dot{z}_2 &= v. \end{aligned} \tag{29}$$

If we now assume that the state x_1 can be measured, and the state x_2 is estimated, following (11), we can design an observer for the system (27) in the following form:

$$\begin{aligned} \dot{\hat{z}}_1 &= \hat{z}_2 - \alpha_1 \tilde{z}_1 - K_1 \mathrm{sgn}(\tilde{z}_1), \\ \dot{\hat{z}}_2 &= -\alpha_2 \tilde{z}_1 - K_2 \mathrm{sgn}(\tilde{z}_1) + L_f^2 h(\hat{x}) + L_g L_f h(\hat{x}) u. \end{aligned} \tag{30}$$

4.2. Sliding mode control design

We will first define the error signal as follows:

$$e = z_{1_{ref}} - z_1, \tag{31}$$

where $z_{1_{ref}}$ represents the reference input signal. The system model (29) can now be represented using the error signal state coordinates by introducing:

$$\begin{aligned} e_1 &= e, \\ e_2 &= \dot{e}_1 = -z_2, \end{aligned} \tag{32}$$

so that the system (29), represented as an error model in the state space, transforms into:

$$\begin{aligned} \dot{e}_1 &= e_2, \\ \dot{e}_2 &= \ddot{e}_1 = -v. \end{aligned} \tag{33}$$

The switching function is chosen as:

$$s = ce_1 + e_2. \tag{34}$$

The sliding surface is defined as $s = 0$ so the system dynamics in the ideal sliding mode defined by $\dot{s} = 0$ described by:

$$\dot{e}_1 = -ce_1. \tag{35}$$

We can now define a control that ensures movement along the sliding. Using Lyapunov's stability theory, we can define the conditions for establishing the sliding mode. If we define the following Lyapunov function as in (16), the system will be stable if the following condition is satisfied:

$$\dot{V} = s\dot{s} < 0. \tag{36}$$

The above inequality also represents the condition for the existence of the sliding mode. In this paper, SMC based on the so-called power rate reaching law, which defines the dynamics of the switching function in both, the reaching and sliding phases [30], is used. The power rate reaching law:

$$\dot{s} = -\beta |s|^{\alpha} \operatorname{sgn}(s), \ 0 < \alpha < 1, \tag{37}$$

minimizes chattering and ensures reaching in finite time. To define the control law, from (34) and (37), we obtain:

$$\dot{s} = ce_2 - v = -\beta |s|^{\alpha} \operatorname{sgn}(s), \tag{38}$$

which gives:

$$v = ce_2 + \beta |s|^{\alpha} \operatorname{sgn}(s). \tag{39}$$

Equation (39) satisfies the conditions for establishing the sliding mode for all values of $\beta > 0$. Considering (34), (36), and (38), we obtain the inequality:

$$s\dot{s} = -s\beta |s|^{\alpha} \operatorname{sgn}(s) = -\beta |s|^{\alpha+1} < 0, \tag{40}$$

which is satisfied for any value of $\beta > 0$.

5. Simulation Results

To verify the performance of the observer and the control law designed as described in the previous sections, simulations were conducted using the MATLAB/Simulink software package. The parameters used for the simulation are given in Table 1. Due to the singularity present at the beginning of the experiment, i.e., when the armature current is zero, its value is lower bounded to $i_{\min} = 0.04\,\text{A}$. The block diagram of the proposed control is shown in Figure 1.

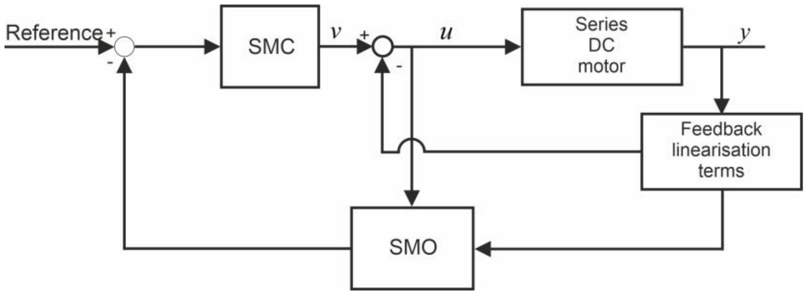

Fig. 1 Block diagram of the proposed control algorithm

Figures 2, 3, 4, and 8 show the simulation results for the case where there is no noise in the system and the reference signal is equal to 1 rad/s. Real and estimated output signals from the series DC motor, i.e., the measured and estimated angular velocity values, are shown in Figure 1. Based on the displayed results, it can be seen that the observer values quickly converge to the measured values of the angular velocity of the series DC motor. Figure 3 shows the model and estimated output signal values. Here, it is also evident that the estimated armature current value from the observer converges to its true value. Figure 4 shows the applied SMC based on the power rate reaching law. It can be observed here that the effect of chattering is eliminated using this control law. Simulation results in the presence of white noise with a standard deviation of 1.0, acting on the state coordinate x_1, are shown in Figures 5, 6, 7, and 9. From Figure 6, it is noticeable that the state coordinate x_2 is very well estimated despite the presence of noise. However, from Figure 7, it can be seen that chattering is present in the control signal.

Table 1 DC motor parameters

Armature inductance	$\mathrm{L} = 0.917\ \mathrm{H}$
Armature resistance	$\mathrm{R} = 7.2\ \Omega$
Viscous friction coefficient	$\mathrm{D} = 0.0004$ Nm/rad/s
Torque constant	$\mathrm{K_t} = \mathrm{K_m L_f} = 0.123$ Nm/WbA
Moment of inertia	$\mathrm{J} = 0.0007046\ \mathrm{kg/m^2}$
Armature current	$\mathrm{I_{min}} = 0.04\,\mathrm{A}$

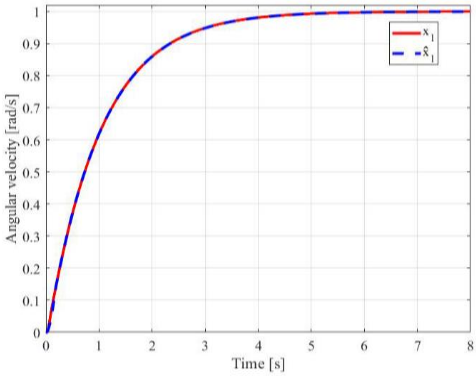

Fig. 2 Angular velocity of series DC motor

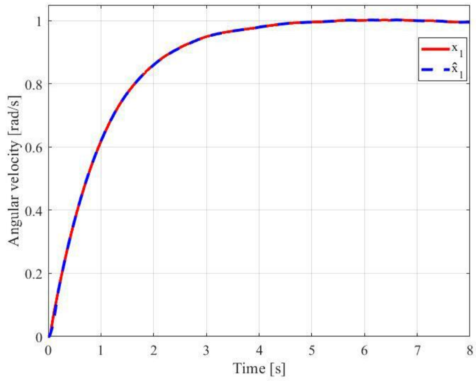

Fig. 5 Angular velocity of series DC motor (with white noise)

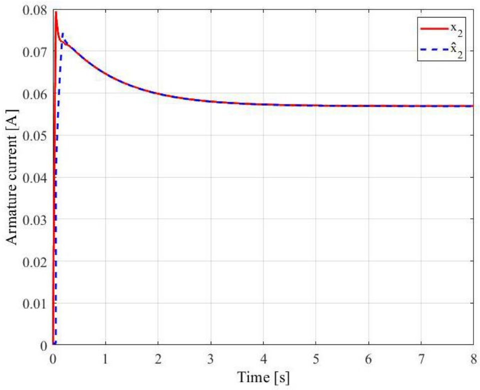

Fig. 3 Armature current of series DC motor

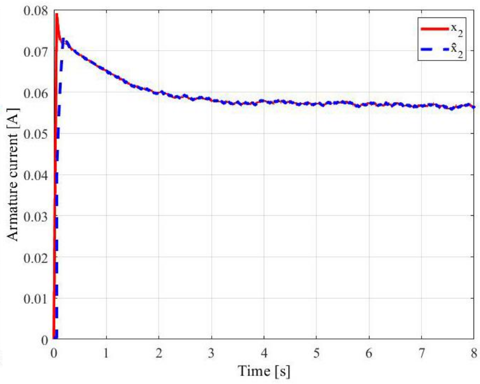

Fig. 6 Armature current of series DC motor (with white noise)

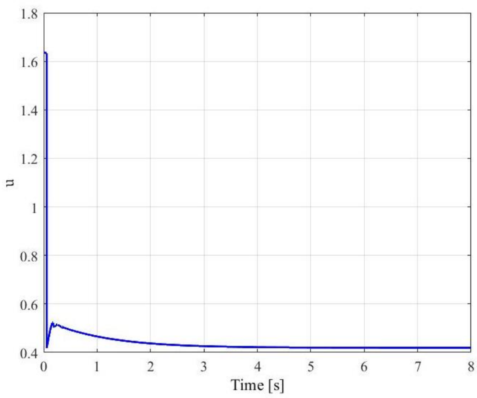

Fig. 4 Control signal

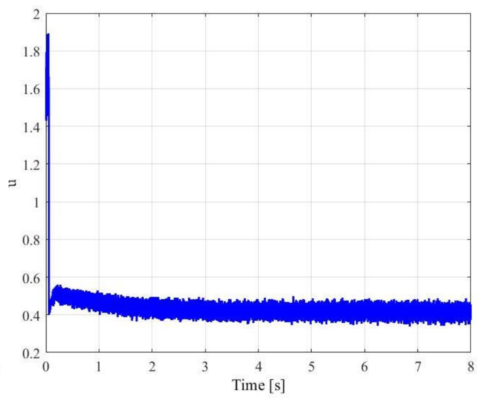

Fig. 7 Control signal (with white noise)

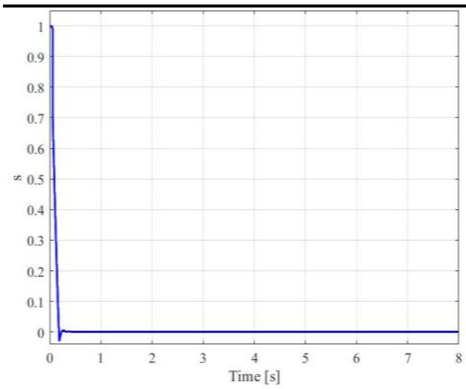

Fig. 8 Switching function

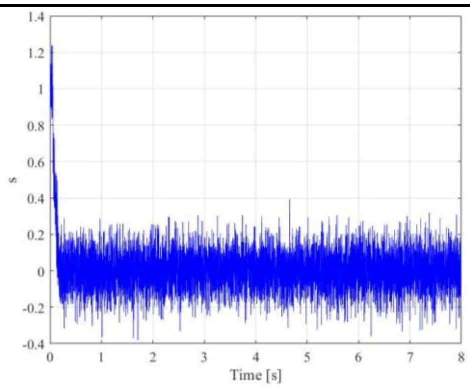

Fig. 9 Switching function (with white noise)

6. CONCLUSION

The combination of the sliding mode control (SMC) and the sliding mode observer (SMO) for the control of nonlinear systems is presented in this paper. It has been shown that the observer design method used in this paper can be applied to nonlinear systems that can be linearized and whose relative degree of freedom is greater than the number of state coordinates. It has also been demonstrated that SMC can be used for the control of these systems. As an example, the nonlinear mathematical model of a series DC motor was used, and the designed control algorithm together with the designed observer was applied. To the authors' knowledge, the combination of SMC and SMO, along with the feedback linearization technique, for a series DC motor has not been studied earlier. To avoid the singularity that occurs at the beginning of the experiment, when the armature current is zero, it was introduced that the minimum value of the armature current is $i_{\min} = 0.04$ AFor linearization, estimated state values obtained from the observer are used. The SMC designed for the control of the series DC motor is based on the power rate reaching law. The main advantage of this control law is the significant reduction of chattering in the control signal as well as in the switching function. It can be seen that chattering is not present if there is no noise in the system. In the presence of noise, based on the obtained results, it is evident that the estimated values from the observer are the same as the measured values; however, it is also noticeable that chattering is now present in the control signal.

Future work will focus on introducing some optimal control laws in order to achieve better system response in practical implementation. Predictive control methods, such as model predictive control (MPC) or sliding mode predictive control (SMPC), are good candidates for this purpose. The implementation of MPC is expected to enhance optimal system performance under the defined system limitations, which is a key feature of predictive algorithms. Meanwhile, SMPC provides the combined benefits of robustness and optimal control.

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