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Design a Second Order Sliding Mode Controller for Electrical Servo Drive Systems

Abstract- *The aim of this paper is to design and study a powerful second-order sliding mode controller for electrical servo drive systems. The suggested controller can successfully overcome the chattering problem that was usually facing such systems during operation. The first (1-SMC) and second (2-SMC) sliding mode controllers are nonlinear controllers' techniques capable of stabilizing the output of a plant, even though a disturbance and parameter uncertainty is present. The asymptotically stable is the significant property of 1-SMC as well as 2-SMC. Despite the robustness of the 1- SMC, in real-time but it suffers from a large settling time and a chattering (undesirable rapid oscillations) of system trajectory close to the sliding surface. The chattering must be reduced because of its negative impact on system stability. The chattering can be reduced by replacing the sign function, used in classical sliding mode, by a saturation function. In the current study, the Second Order Sliding Mode Controller (2-SMC) is used to overcome the drawbacks of 1- SMC by reducing both the chattering and the settling time of the control action. The Electrical Servo drive system was adopted in this paper for testing; both, the 1-SMC as well as the 2-SMC. The comparison of results between the two controllers indicated smaller chattering and settling time in the 2-SMC than that in the 1-SMC. The simulation results of this work were obtained by using the Matlab programming.*

Keywords- *Chattering, first order sliding mode controller, second order sliding mode controller, asymptotically stable, Electrical Servo drive.*

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1. Introduction

In the last few years, many techniques for controlling linear and nonlinear systems take much attention from researchers, and as a result, many strategies were presented [1]. One of the most significant methods is the Sliding Mode Controller (SMC), which is considered an efficient and powerful control method that lately widely used in many different applications. The SMC is characterized by its ability to controlling dynamical and physical systems in the existence of parameter uncertainty and external disturbances that are affecting the performance of the system. The SMC is insensitive to them [2]. Despite of the SMC advantages, but it is still suffered from a major problem called chattering, which is considered an unwanted phenomenon. To decrease the chattering in the SMC, many techniques were presented to overcome this undesired property. One of these methods is by utilizing a saturation function instead of a sign function in the SMC [3]. Other authors proposed to combine fuzzy logic with a SMC to obtain a "sliding mode fuzzy controller (SMFC)" to reduce the chattering problem [4]. Some authors utilized a genetic algorithm to improve the standard the first-order sliding mode controller [5]. Moreover, others were proposed to utilize the particle swarm optimization technique to decrease the chattering problem [6]. The main characteristics of the SMC are that the order of the original system is reduced by one, and the simplicity in operation [7]. In the Sliding mode control, the system states are moving by control law toward the sliding manifold and then constrained in it. In [8], Emel' yanov was initially introduced the concept of acting on the sliding variable that has higher derivatives and presented the second-order sliding mode algorithms (2-SMC), such as twisting algorithm and super twisting algorithm. The 2-SMC approach is an efficient solution to the above disadvantages that 1-SMC suffered from [9]. The algorithms of 2-SMC are used to guarantee the robustness control against parameter uncertainty and disturbances as well as to achieve minor convergence of sliding variables [10]. In this paper, the behavior of electrical servo drive systems will be improved by using the 2-SMC algorithms in order to reduce the chattering that is existed in 1-SMC, and the results show the validity of this controller.

2. Standard First Order Sliding Mode Controller (1-SMC)

In fact, many systems are influenced by the parameters of uncertainty and disturbances.

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Controlling the systems in the existence of perturbation is very difficult. The researchers are developed many controllers that working successfully in the existence of these perturbations. Such as the sliding mode controller, which is a robust technique that received large interest because it is unaffected by the variation of parameters and disturbances and ensures the stability of the system. The SMC has been developed first in the 1950s. Recently the sliding mode controllers are widely used in different applications like power electronics, robotics, and others. Despit the robustness, the SMC suffered from an essential drawback known as “chattering,” which is described as high frequency leads to unwanted oscillations that affect the control action in the system. This problem can reduce the performance of the system or make it rise to instability. The chattering problem can be reduced by using different methods, as mentioned in [4-6]. The designing of the SMC consists of two steps, (1) the construct of a sliding surface and (2) the construct of the control law.

The Sliding Mode Controller consists of two phases [2], as explained below:

A: Reaching phase: during this phase, the state trajectory is steering toward the sliding surface $S = 0$. In this phase, the system is sensitive to different types of perturbations. When the state trajectory arrived at the sliding surface another phase gets started called sliding phase, as shown in Figure 1.

B: Sliding phase: during this phase, the state trajectory is forced to slide on the sliding surface and to move on this surface until it arrived at the origin as displayed in Figure 1.

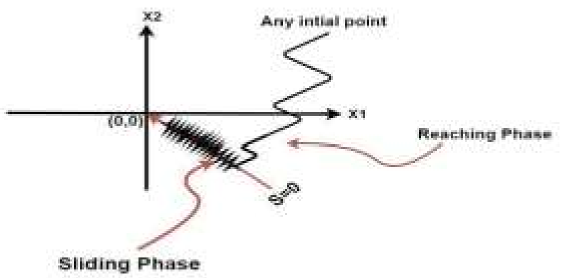

Figure 1: The two phases of the SMC [3].

The general equation of control law is given by:

$$u = u_{eq} + u_{dis} \tag{1}$$

Where, u_{eq} is the equivalent control term responsible for steering the state trajectory of the system towards the sliding surface ($S = 0$) and u_{dis} is the discontinuous control term to constrainthe state trajectory to move straight on the surface until reaching the origin. The equation u_{dis} is given by [11]:

$$u_{dis} = -k(x)\,\mathrm{sign}(s) \tag{2}$$

Where, k is a constant gain with $k > 0$.

The signum function sign(s) is shown in Figure 2 below and is described as below [7, 13]:

$$\mathrm{sign}(s) = \begin{cases} +1 & s > 0 \\ -1 & s < 0 \\ 0 & s = 0 \end{cases} \tag{3}$$

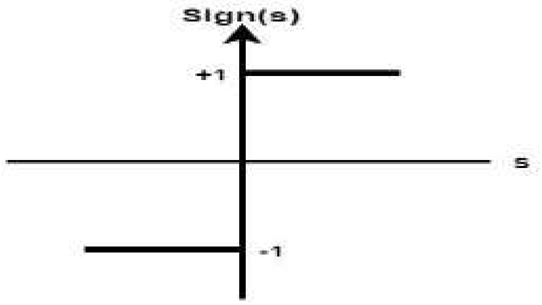

Figure 2: Signum function [4].

By substitute Eq. (2) in Eq. (1), the result control law becomes as below:

$$u = u_{eq} - k(x)\mathrm{sign}(s) \tag{4}$$

The sliding surface is described as:

$$s = \lambda e + \dot{e}\ ;\ \lambda > 0 \tag{5}$$

Where, λ is a constant with $\lambda > 0$,
e is the error and $\dot{e}$ is the derivative of the error.

The error and its derivative are described as:

$x_1 = e = \theta - \theta_f$ And $x_2 = \dot{e} = \dot{\theta}$

Where θ_f represent the final desired position.

Equation (5) can be rewrite as below:

$$s = \lambda x_1 + x_2 \tag{6}$$

When λ=1, Eq. (6) is rewritten as below:

$$s = x_1 + x_2$$

The derivative of sliding surface is:

$$\dot{s} = \dot{x}_1 + \dot{x}_2 \tag{7}$$

The main purpose of the SMC technique is to design a robust controller that can be able to orient the sliding variable toward the manifold surface and keep the system trajectory in this required sliding surface [7, 12].

In the above Eq. (4), the discontinuous control involves the term (sign(s)), which is caused by a chattering. This chattering is described as unwanted property appearing along the sliding surface because it is reduced the system stability. The chattering is considered as a severe problem in Sliding Mode Control system.

To reduce the unwanted chattering, the saturation function sat(s) can be used instead of the signum function $\mathrm{sign}(s)$ in control law of Eq. (4). The saturation function is shown in Figure 3, and it is described, as below [7, 13]:

$$\mathrm{sat}(s/\varphi) = \begin{cases} +1 & (s/\varphi > 0) \\ s/\varphi & (-1 < s/\varphi < 1) \\ -1 & (s/\varphi < 0) \end{cases}$$
(8)

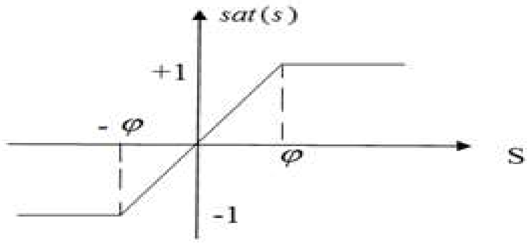

Figure 3: The saturation function [4].

Equation (9) below shows the final control law after putting sat(s) instead of sign(s):

$$u = u_{eq} - k(x)\mathrm{sat}$$
(9)

3. Second-Order Sliding Mode Controller (2-SMC)

The Second-order sliding mode control (2-SMC) is a powerful nonlinear controller method that can be used to decrease the chattering of the standard first-order sliding mode controller. In [8]، Emel' yanov is the first one who developed the concept of acting on the high order derivatives of the switching variable **S,** and as a result, the second-order sliding algorithms were developed. In recent years, the second-order sliding mode control received significant interest from researchers, because it is considered as an efficient solution to the drawbacks of the 1-SMC [9]. The main characteristic of this control technique is the finite-time convergence of the sliding variable and its first derivation to the origin [12].The second-order SMC not only preserves the main features of the conventional 1-SMC but also reduces the chattering influence and improves the system performance, such as reducing the settling time of the control action. Many authors have participated in developed numerous 2-SMC algorithms, such as twisting algorithm and super twisting algorithm and other. The twisting algorithm is un easiest 2-SMC algorithm, where the super twisting algorithm gives better results than the twisting algorithm as well as the 1- SMC [13]. The 2-SMC is utilized to guarantee not only robustness against perturbations but also by reducing the chattering as well as to ensure a finite-time stabilization of the sliding variable S and its first derivative $\dot{S}$ [10]. In the second-order sliding mode, the state trajectories will be on the sliding surface if and only if they are moved in the intersection area between the two surfaces S=0 and $\dot{S}$=0 [10, 14]. The constraint of the 2-sliding mode is as described below [10]:

$$S = \dot{S} = 0$$
(10)

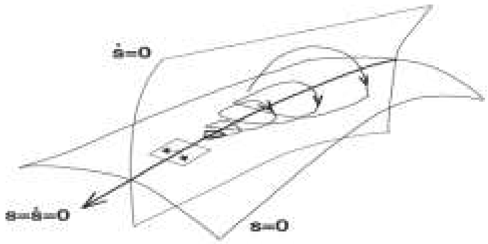

Figure 4: The second order sliding mode trajectory [10].

The 2-SMC can be obtained by taking the second derivative of sliding variable S [8]. The essential problem in 2-SMC is the stabilization of $\ddot{S}$. The term $\dot{u}$ in Eq. (11) below, represents the discontinuous actual control that will orient S and $\dot{S}$ to zero. Therefore, the system control u is representing the continuous control and as a result, the chattering is reduced [14].

$$\ddot{s} = \varphi(t,x) + \gamma(t,x)\,\dot{u}$$
(11)

The conditions of $\varphi(t,x)$ and $\gamma(t,x)$ functions are:

$$|u| \le U_m$$
$$0 < \Gamma_m < \gamma(t,x) < \Gamma_M$$
(12)
$$|\varphi(t,x)| < \Phi$$

Where,U_m, Γ_m, Γ_M and Φ are constants greater than zero.

In following some algorithms of 2-SMC is listed below:

I. Super- twisting algorithm

This algorithm is Presented, by Levant in 1993 and it can be used for stabilizing the systems with a relative degree only one. The trajectories in this algorithm are converging to the origin by turning around it, as shown in Figure 5 below [10]. The control law of this algorithm consist of two parts; the first part is the continuous function, while the second is the integral of the discontinuous function [8].

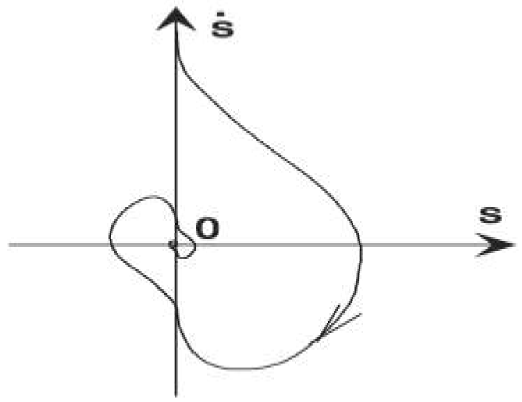

Figure 5: The super twisting algorithm trajectory in (s,ṡ) plane [10].

The super-twisting algorithm is defined as:

$$u_{dis} = -\lambda|s|^{\rho}\mathrm{sign}(s) + \int -W\,\mathrm{sign}(s)dt \quad (13)$$

Where the parameters, λ, W and ρ will be determined from the following conditions:

$$W > \frac{\Phi}{\Gamma_m}$$

$$\lambda^2 \geq \frac{4\Phi}{\Gamma_m^2}\frac{\Gamma_M(W+\Phi)}{\Gamma_m(W-\Phi)} \quad (14)$$

Where $0 < \rho \leq 0.5$

The complete control action u can be obtained by substituting Eq. (13) in Eq. (1).

II. The twisting algorithm

The different of this algorithm from the super twisting algorithm is, the twisting algorithm can be utilized for stabilizing the systems with relative degree one as well as two. The trajectory of this algorithm is turning around the origin until it reaches it, as shown in Figure 6 below [13, 14].

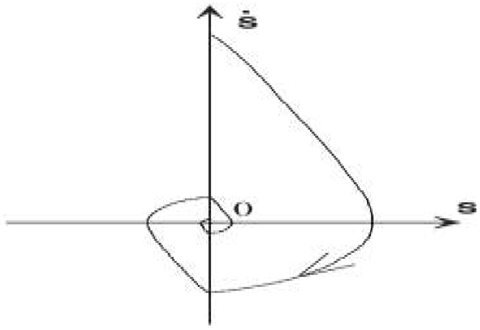

Figure 6: The trajectory of twisting algorithm in (s, ṡ) plane [10].

The twisting algorithm is defined by:

$$u_{dis} = -k_1\mathrm{sign}(s) - k_2\mathrm{sign}(\dot{s}) \quad (15)$$

With positive values of k_1 and k_2 and must satisfying the condition that $k_1 > k_2$.

4. Electrical Servo Drive Description

The electrical servo drive is a linear system that is used in many engineering systems. The essential characteristics that are required for this system are to have high robustness, good performance, high tracking, and fast response. The second-order equation of the electrical servo drive system is defined as below [15]:

$$\ddot{\vartheta} = -\frac{B}{J}\dot{\vartheta} + \frac{k_t}{J} * u + \frac{1}{J}Td \quad (16)$$

Where the definition of the parameters of the above equation are as below;

ϑ: The position of the rotor (radian),

$\dot{\vartheta}$: The angular velocity (radian / sec.),

$\ddot{\vartheta}$: The angular acceleration (radian / sec^2),

J And B: are the moment of inertia and the damping coefficient,

u: The control action command (ampere),

k_t: The torque constant,

Td: The external disturbance (N. m),

The parameters value of the electrical servo drive system is listed in Table 1.

Table 1: The nominal values of the parameters of the electrical servo drive system.

Parameters	Nominal value	Units
B	$8.8*10^{-3}$	Nm^2/rad
J	$5.77*10^{-2}$	Nms^2
$\mathbf{k_t}$	0.667	Nm/A

In this paper, a particular system was adopted; therefore, Td was assumed to be zero (Td=0).

The error and the derivative of the error of the electrical servo drive system can be defined in state-space form as below:

$$x_1 = e = \vartheta - \vartheta_f$$

$$x_2 = \dot{e} = \dot{\vartheta}$$

Where ϑ_f represent the required final position.

The above equations can be rewritten as:

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = -\frac{B}{J}x_2 + \frac{K}{J}u \quad (17)$$

Case one: Design the standard first-order sliding controller (1-SMC) for the electrical servo drive system

The first order sliding mode controller for the above system can be designed by subtitling Eq. (17) in Eq. (7) to find the control action u from this equation, which represents the equivalent control u_{eq} and then by subtitling u_{eq} in Eq. (4), the complete control action will be described as below:

$$u = \frac{J_n}{k_t}\left(x_2\left(\frac{B_n}{J_n} - \lambda\right)\right) - k * sign(s)$$
(18)

In order to attenuate the chattering effect, the signum function sign(s) in the Eq. (18) will be replaced by saturation function sat(s) as shown in Eq. (19) below:

$$u = \frac{J_n}{k_t}\left(x_2\left(\frac{B_n}{J_n} - \lambda\right)\right) - k * sat(s)$$
(19)

Case two: Design the second order sliding mode controller (2-SMC) by using the super twisting and twisting algorithms for electrical servo drive system.

I. The super twisting algorithm

By taking the second order derivative of sliding variable s

$$\ddot{s} = -\frac{B}{J}\left(-\frac{B}{J}x_2 + \frac{K}{J}u\right) + \frac{K}{J}\dot{u}$$
(20)

From Eq. (20), $\varphi(t,x) = -\frac{B}{J}\left(-\frac{B}{J}x_2 + \frac{K}{J}u\right)$ and $\gamma(t,x) = \frac{K}{J}$. These two functions are bounded and both are limited by the following two conditions.

$0 < \Gamma_m < \gamma(t,x) < \Gamma_M$ And $|\varphi(t,x)| < \Phi$.

Because the value of Φ is very complicated to calculate, therefore it will be assumed to be 5.5. Where the values of Γ_m and Γ_M are obtained from Eq. (12), as below:

Γ_m=10.5 and Γ_M=12.5.

The super twisting algorithm is

$$u_{dis} = -\lambda|s|^{\rho} sign(s) + \int -W\, sign(s)dt$$

The values of λ, W and ρ are determined from Eq. (14), and there values are

$\lambda = 1$, $W = 11$ and $\rho = 0.1$

Finally, the complete control action u of this algorithm can be obtained as below:

U= u_{eq}+u_{dis}

II. The twisting algorithm

The discontinuous control of this algorithm is described by

$$u_{dis} = -k_1 sign(s) - k_2 sign(\dot{s})$$

With the condition $k_1 > k_2$

In this paper the values of k_1 and k_2 are choose as below

k_1= 0.5 and k_2= 0.05.

The complete control law of this algorithm is:

U= u_{eq}+u_{dis}

5. The Simulations Result

Case (A): The results when using sign function

1: The first order sliding mode controller (1-SMC) with a sign function

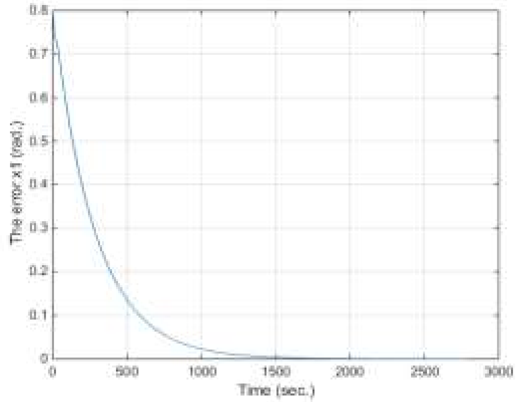

Figure 7: The error x_1 vs. time.

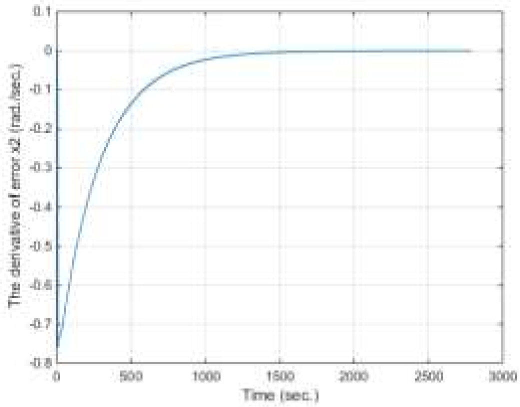

Figure 8: The derivative of error x_2 vs. time.

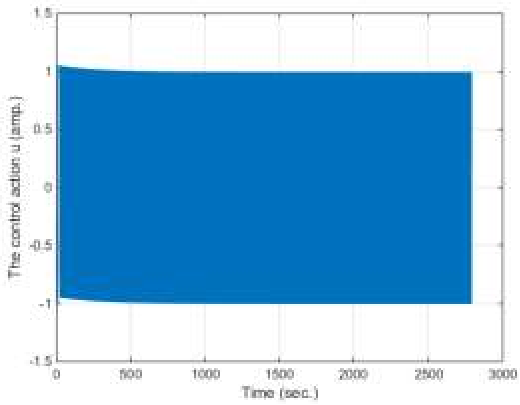

Figure 9: The control action u vs. time.

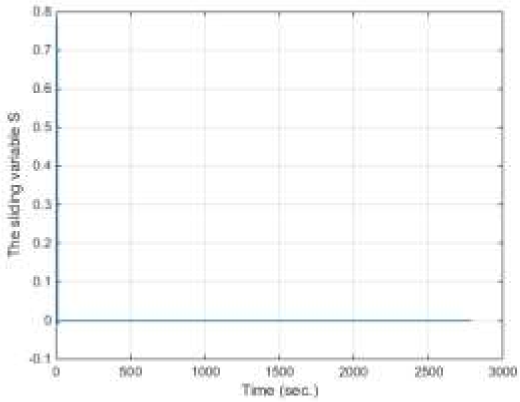

Figure 10: The sliding variable S vs. time.

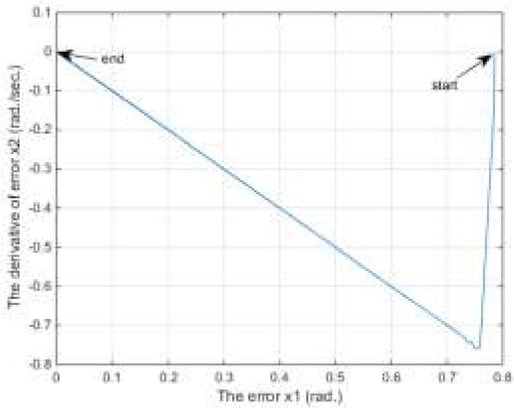

Figure 11. The derivative of error x_2 vs. the error x_1.

2: The second order sliding mode controller (2-SMC) with a sign function

a) The Super twisting algorithm

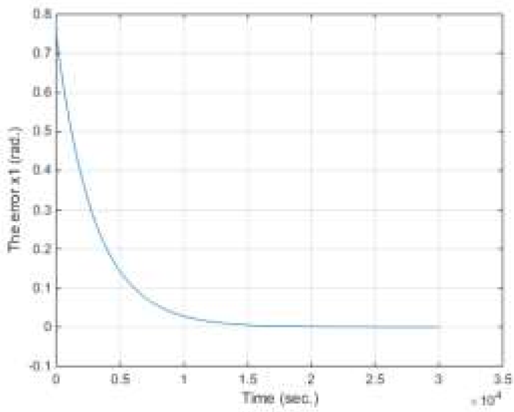

Figure 12: The error x_1 vs. time.

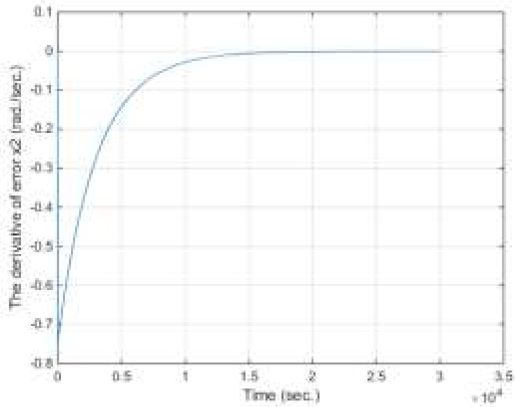

Figure 13: The derivative of error x_2 vs. time.

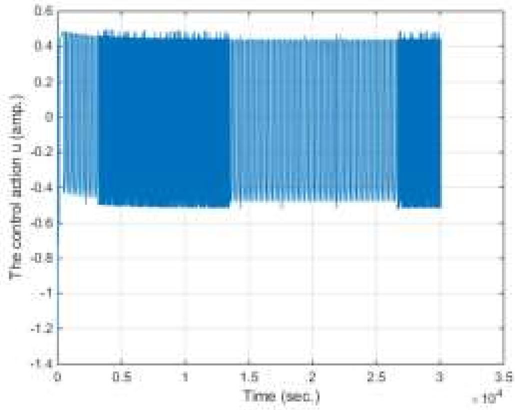

Figure 14: The control action u vs. time.

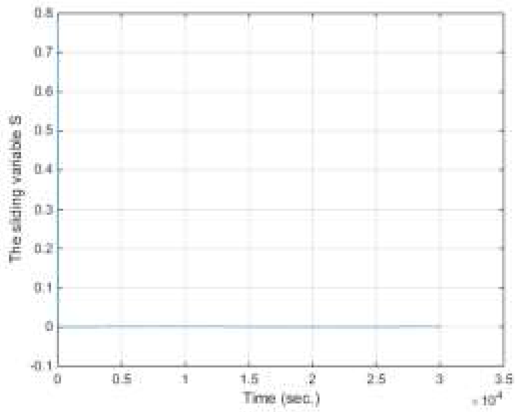

Figure 15: The sliding variable *S* vs. time.

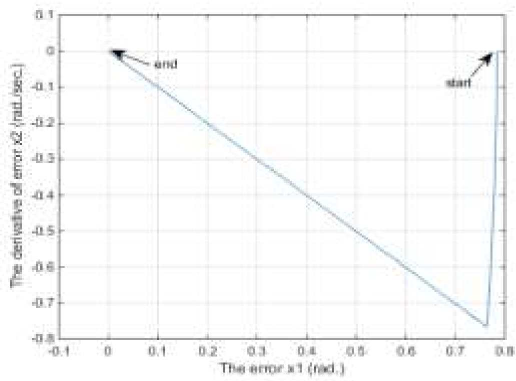

Figure 16: The phase plane between x_2 and x_1.

b) The Twisting algorithm

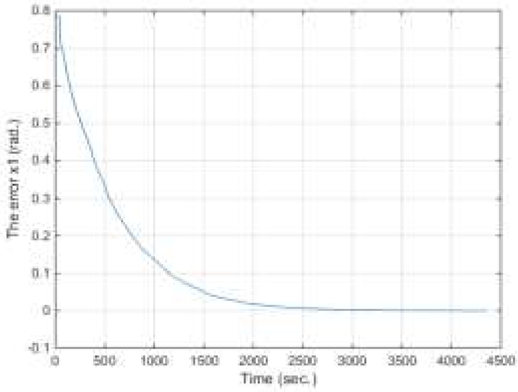

Figure 17: The error x_1 vs. time.

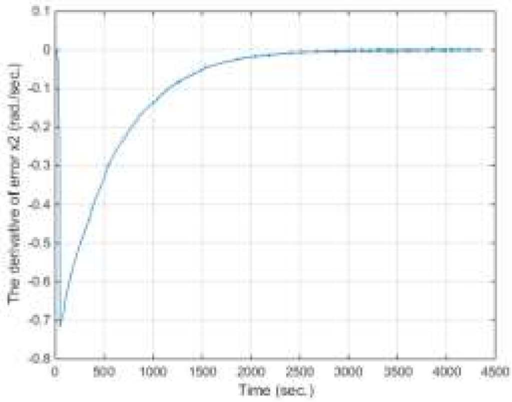

Figure 18: The derivative of error x_2 vs. time.

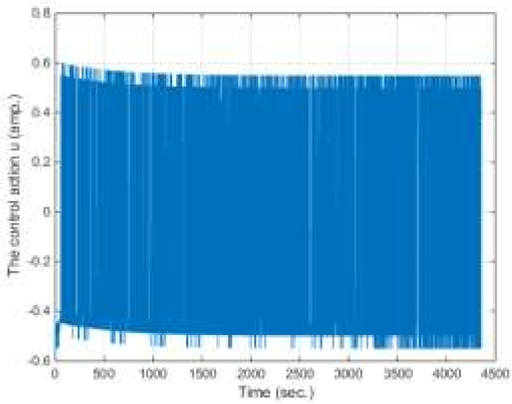

Figure 19: The control action vs. time.

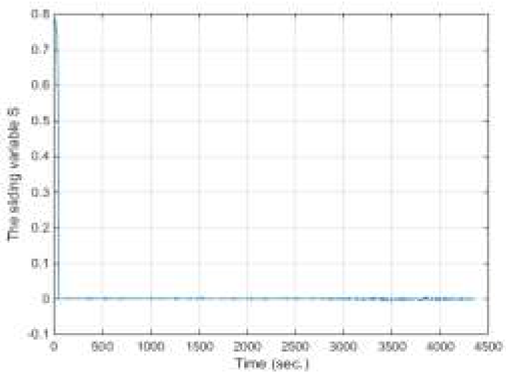

Figure 20: The sliding variable s vs. time.

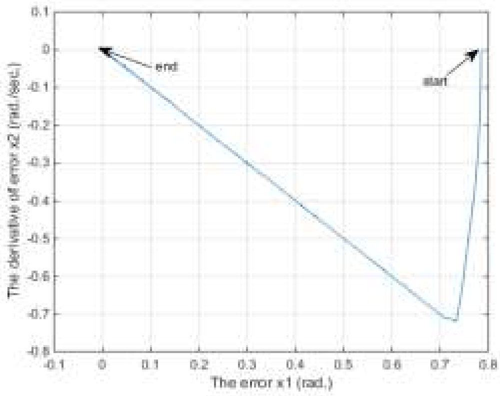

Figure 21: The derivative of error x_2 vs. the error x_1.

Case (B): The results when using saturation (sat) function

1: The first order sliding mode controller (1-SMC) with sat function

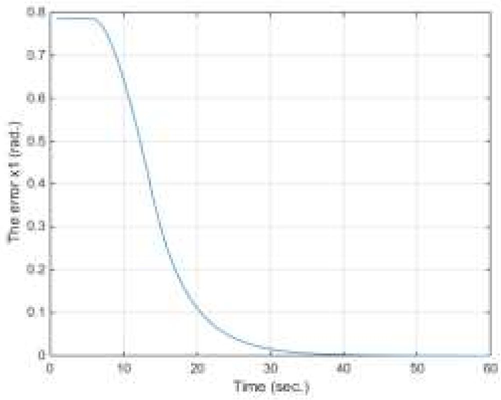

Figure 22: The error x_1 vs. time.

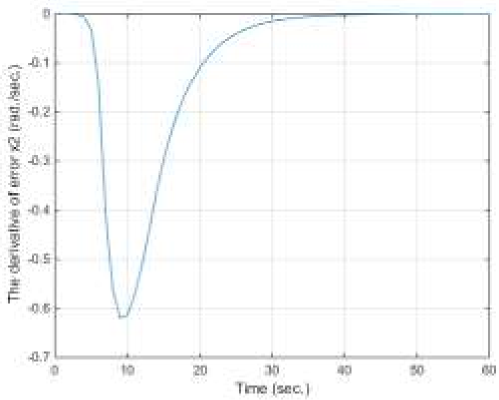

Figure 23: The derivative of error x_2 vs. time.

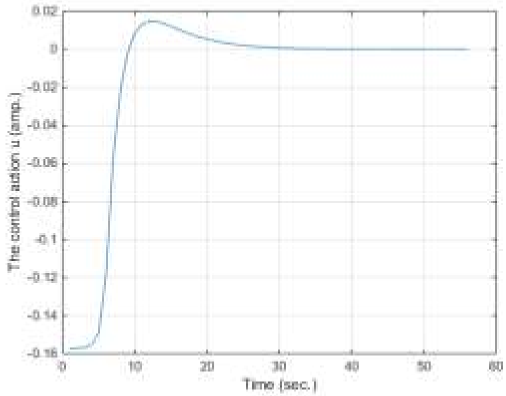

Figure 24: The control action u vs. time.

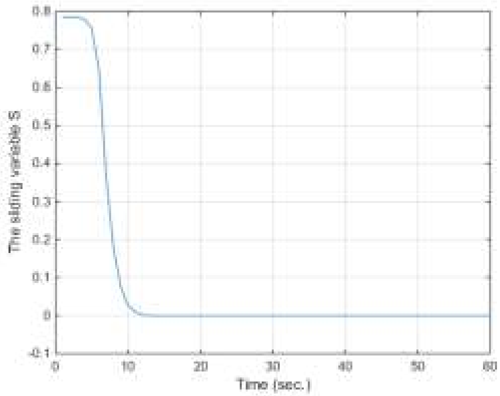

Figure 25: The sliding variables vs. time.

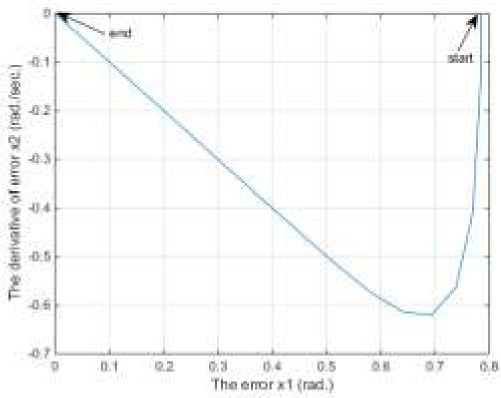

Figure 26: The derivative of error x_2 vs. the error x_1.

1) The second order sliding mode controller (2-SMC) with sat function

a) The Super twisting algorithm

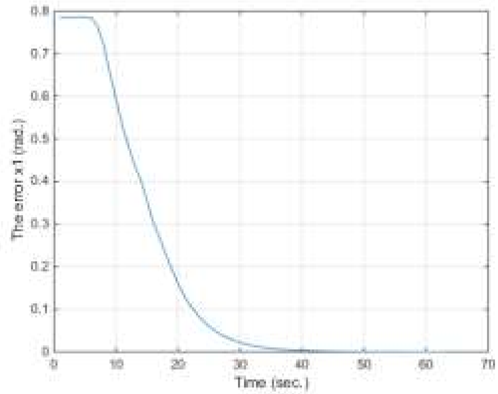

Figure 27: The error x_1 vs. time.

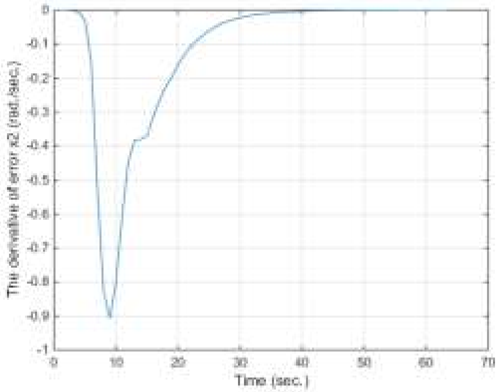

Figure 28: The derivative of error x_2 vs. time.

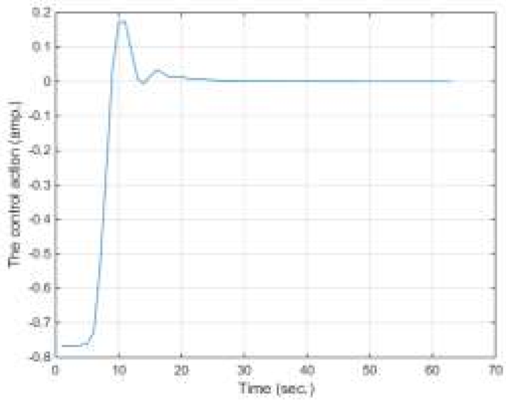

Figure 29: The control action vs. time.

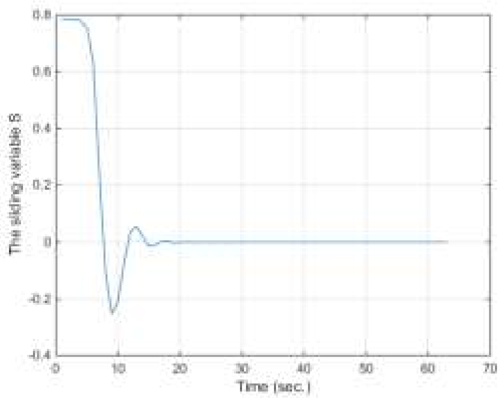

Figure 30: The sliding variable s vs. time.

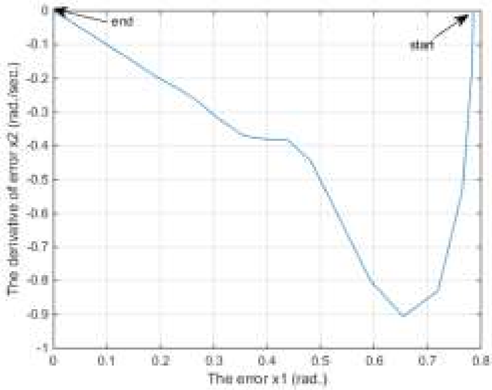

Figure 31: The derivative of error x_2 vs. the error x_1.

b) The Twisting algorithm

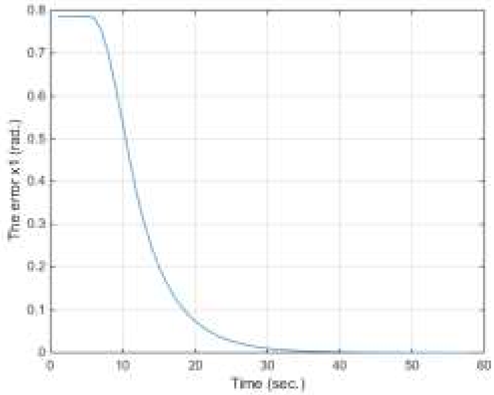

Figure 32: The error x_1 vs. time.

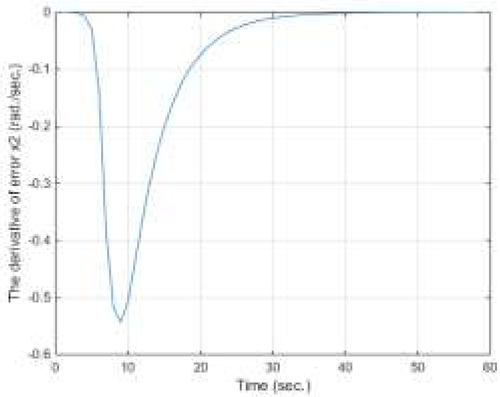

Figure 33: The derivative of error x_2 vs. time.

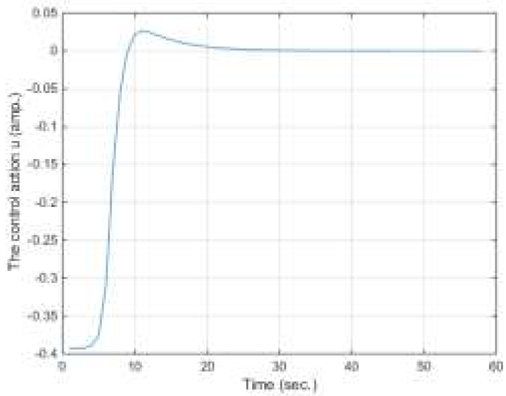

Figure 34: The control action u vs. time.

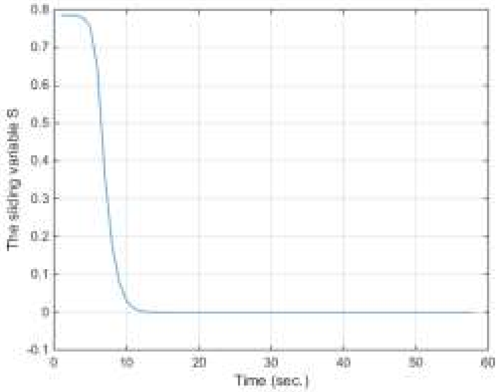

Figure 35: The sliding variable s vs. time.

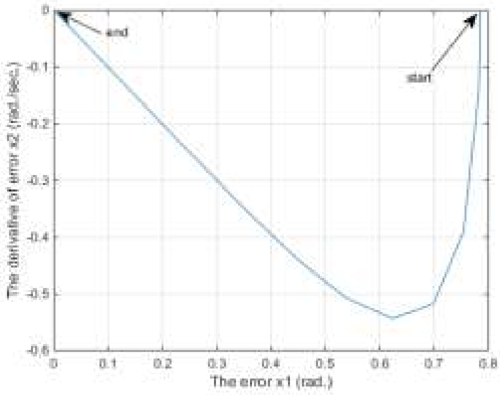

Figure 36: The derivative of error x_2 vs. the error x_1.

6. Discussion

This work-study the performance of 1-SMC and 2-SMC, which are both applied to an electrical servo drive system to show the difference between them. The first order sliding mode controller was good at the beginning to control the position of electrical servo drive, but this controller suffered from a major disadvantage called chattering. The effect of the chattering will appear in the control signal u and the sliding variable S as shown in Figures 9 and 10; as a result, it affects the stability and performance of the system. This paper, the 2-SMC, has been used instead of 1-SMC in order to reduce the chattering of 1-SMC, which come from the existence of sign (s) function in the discontinuous control. The reduction of chattering was observed in Figures 14 and 19 by using the two algorithms of 2-SMC. By using the two algorithms of 2-SMC, the convergence of system states to the origin was satisfied, as shown in the phase plane Figures 16 and 21. This 2-SMC can also able to reduce the settling time of the control action u in comparison with 1-SMC, as shown in table 6.2, and as a result, the stability is improved. As well as the previous advantage, the 2-SMC is maintaining the essential advantages of 1-SMC, such as the robustness and also by making the system asymptotically stable. It is noted from the simulation results that the super twisting algorithm is the best one among the other algorithms since it can reduce the magnitude of the chattering in both the control action u and the sliding variable S as shown in Figures 14 and 15, respectively. The 2-SMC can also reduce the settling time of the control action u as shown in Figure 29. Tables 2 and 3 show the difference between the three controllers in the magnitude of chattering and settling time.

Table 2: The effect of using the sign function on the magnitude of chattering when using different controllers

Controllers type	Magnitude of Chattering
1-SMC	2
2-SMC Twisting	1.1
2-SMC Super twisting	0.82

Table 3 shows the effect of using the sat(s) function instead of the sign(s) function in the above three controllers to reduce the chattering more than before and to get better performance as shown in the Figures 24, 29 and 34.

Table 3: The effect of using the sat function in settling time and chattering.

Controllers type	Settling time of control action u (Sec.)	Magnitude of chattering
1-SMC	30	0.001
2-SMC Twisting	25	Approximately equal zero
2-SMC Super twisting	22	Approximately equal zero

7. Conclusion

In this paper, the second-order sliding mode controller with two algorithms (twisting and super twisting algorithm) is adopted to improve the performance of 1-SMC in the electrical servo drive system. It is concluded from the above simulation results that the 2-SMC can reduce the chattering in the control action that exists in 1-SMC despite using the sign (s) function, which is the reason of existing the chattering problem, and the 2-SMC can improve the accuracy of the system. The 2-SMC can also reduce the settling time and the chattering of the control signal when using the sat (s) function instead of sign (s) as shown in table 6.2. It is concluded from comparing Figures 9, 14, and 19 that the super twisting algorithm is the best one on reducing the chattering that is present in the control signal. The aim of this work is achieved by proving that the 2-SMC is better than 1-SMC.

References

[1] C.A. Yfoulis, A. Muir, and P.E.Wellstead, “A New Approach for Estimating Controllable and Recoverable Regions for Systems with State and Control Constraints,” *International Journal of Robust and Nonlinear Control*, Vol. 12, No. 7, pp. 561-589, 2002.

[2] S. Mondal, “Adaptive second order sliding mode control strategies for uncertain systems,” Ph. D. thesis, Department of Electronics and Electrical Engineering, Indian Institute of Technology Guwahati, pp. 2-155, 2012.

[3] V.I. Utkin, J. Guldner, and J. Shi, "Sliding Mode Control in Electromechanical Systems,” CRC Press. Taylor & Francis Group, 2009.

[4] A.K. Hamoudi, “Design and Simulation of Sliding Mode Fuzzy Controller for Nonlinear system,” *Journal of Engineering, College of Engineering*, University of Baghdad, Vol. 22, No. 103, pp. 66-76, 2016.

[5] A.K. Hamoudi, “Sliding Mode Control for Non linear system best on Genetic Algorithm,” *Journal of Engineering and technology*, Vol. 32, No. 11A, pp. 2745-2759, 2014.

[6] Z. Chen, W. Meng, Z. Wang and J. Zhang, “Sliding Mode Variable Structure Control Based on Particle Swarm Optimization,” Second International Symposium on Intelligent Information Technology Application, Taiyuan, China, pp. 692-696, 2008.

[7] H. Lee and V.I. Utkin, “Chattering Suppression Methods in Sliding Mode Control Systems,” Annual Reviews in Control, Vol. 31, No. 2, pp. 179-188, 2007.

[8] M.K. Khan, “ Design and application of second order sliding mode control algorithms,” Ph. D. thesis, Department of Engineering University of Leicester, pp. 5-172, 2003A.

[9] A. Pisano, “Second Order Sliding Modes: Theory and Applications,” Ph.D. Thesis, Department of Electronics and Electrical Engineering, Cagliari university, pp. 6-123, 2000

[10] O. Jedda, J. Ghabi, A. Douik, “Second Order Sliding Mode Control for Inverted Pendulum,” *International Journal, University of Monastir and University of Sousse*, pp. 1-5, 2015

[11] A.K. Hamoudi, N.O. Abdul Rahman, “Design an Integral Sliding Mode Controller for a Nonlinear System,” *Al-Khwarizmi Engineering Journal*, Department of Control and Systems Engineering/ University of Technology, Vol. 13, No. 1, pp. 138-147, 2017.

[12] J. Huspeka, “Second order sliding mode control of the DC motor,” *International journal on process control,* Department of Cybernetics, Faculty of Applied Sciences,

University of West Bohemia, pp. 134-139, 2009.

[13] S. Ding and J. Wang, "Second-Order Sliding Mode Control for Nonlinear Uncertain Systems Bounded by Positive Functions," *journal, Electrical and Information Engineering University of Science and Technology*, VOL. 62, NO. 9, pp. 5899-5908, 2015.

[14] G. Bartolini, A. Ferrara, A. Levant, E. Usai, "On Second Order Sliding Mode Controllers," *journal, Department of Electrical and Electronic Engineering_ University of Cagliari,* Department of Communication_ Computer and System Sciences_ University of Genova, pp. 2-22, 2007.

[15] H.P. Pang and Q. Yang, "Optimal Sliding Mode Control for a Class of Uncertain Nonlinear Systems Based on Feedback Linearization," Qingdao University of Science and Technology, Robust Control, Theory and Applications, pp. 142-162, 2011.