RT&A, No 4 (71)
Volume 17, December 2022

Second Order Sliding Mode Control for Robust Performance of the Systems

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Abstract

An integral PID control sliding surface with first order filter is proposed in this paper to the systems with single-input single-output (SISO). In this The developed sliding mode controller results well, even though there are differences in the model of the system via parametric uncertainty. To verify its applicability to disturbances, the presented work validates the controller performance with the application of an external load. An integral and filtered type sliding surface has advantages in terms of the stability of the systems. The proposed controller properties of stability and robustness are proven by the Lyapunov's stability theorem. By the adoption of switching gain with predetermined parameters of system, the chattering problem phenomenon is greatly minimized. Therefore, the proposed controller in this work is appropriate for extended use in real world systems. In this method proposed control is verified using simulation examples and results for its performance. It will be compared to a similar controller shown in the previous literature work.

Keywords: Integral sliding mode control, Robustness, Stability, Uncertain systems

1. Introduction

Most real-world applications involve non-linear systems, but for analytical and control purposes these are approximated by linear systems. The control for systems composed of the specifications of parameter inaccuracy, that is, the structured uncertainty of the system, the neglected dynamics of unstructured uncertainty, and the generally approximated time delay impose serious challenges to controller design. [1]. The nonlinear controller design techniques, like feedback linearization and sliding mode control are proved to be promising and applicable in control issues includes only an approximate linear description of the system [2, 3]. The sliding mode control (SMC), recommended in initial phase of the early 1950s, validated with ability to handle framework uncertainties and outside disturbances with greater strength [4]-[6]. The dynamic behaviour of system can be modified with the system specifications by the suitable selection of switching of oscillatory function with the SMC method.

In literature, one of the major application of sliding mode control is to limit the effects of external disturbance present in th uncertain systems. control, as presented in the international literature developed earlier in Russia [5]. There are so many sliding mode theories are available in the literature. In the initial study, the focus is on conventional or traditional sliding modes. Traditional SMCs use approximate system models to provide a systematic design procedure [7].Therefore, they are widely used in industries with applications including power electronic converters, position or speed control and robotics, space technology applications, and power converters [8]. Conventional SMCs are popular because of their robustness to modelling errors and their insensitivity to external disturbances and parameter changes [9]. However, in many practical applications, the problem in the control action of vibrations known as chattering occurs because of the SMC design. Chattering is a high-frequency (theoretically infinite frequency) switching in control input because of the unmodeled system dynamics. The high frequency oscillations in control signal called chattering occurs due to discontinuous control term is dangerous, specially, in the systems with mechanical parts. The chattering causes undesired overuse of the actuators and final control elements and also results in system instability [10]. The advances in digital control technology has impacted attention of highly robust controller such as SMCs because it can be easily implemented in digital systems such personal computer or can be implemented in discrete domain [11]- [12]. However, if SMC is designed in discrete mode, the discrete control law of discontinuous or switching term, not only induces chattering phenomenon but it drives the system to be unstable due to infinite sampling rate, and the sampling rate due to infinity may be distant. This can be answered by making the discontinuous term value very small [11]. In literature, for state regulation [13, 14, 15, 25] or for set-point tracking [16, 17, 7, 11, 27] either continuous or discrete SMCs are designed . In literature, it is common that, the concerned researchers have developed a continuous-time sliding mode controller (CSMC) or discrete time sliding mode controller (DSMC)that tracks the setting value considering specific application [33]. Among them, Tannuri et al. [19] and Lee et al. [20] reviewed the positioning control system application, and Orr et al. [21] and Lu et al. [22] has prepared a CSMC for spacecraft applications. tn the Mihoub et al. [23] work furnished, a DSMC with the phase variable state model of second order, for tracking of semi-batch reactors. Eker's research mainly focuses on use of traditional SMC or second order SMC for the speed control application of electromechanical system [16, 17, 26]. Recent contribution by Furat and Eker in development of second order integral SMC for the speed control of electromechanical system through experimental application [24] for the reduction of chattering including robustness to disturbances and uncertainties. In this work, a simple SMC algorithm based on the PID with a first-order filter sliding surface was developed. This developed algorithm is used to tune a general system with second order behaviour. Considering the basic second order model (or an identified second order model), an equivalent or continuous controller is designed with the help of sliding surface parameters and model parameters. It is easy to synthesize and implement a new simple sliding-mode controller with the help of filter parameter λ and PID parameters like K_p, K_i, K_d which can consider for plant uncertainties. In meeting the sliding condition of controller of the closed loop system, the system behaviour and the robust stability are investigated. The scheme presented in this paper is further extended to systems capable of handling the inverse response process. The control application for the FOPDT framework is additionally included as a unique case in a similar manner. The usefulness and applicability of the method proposed is being carefully studied and assessed through several general processes.It also includes performance comparison with few current sliding mode control methods as reliable evaluation criteria.

In the real system instead, the controllers are used in a continuous time domain, as we use microprocessors or computer systems in general. Recently, among the researchers involved in introducing continuous SMC to a discrete time SMC. In the literature, it was discovered that much of the work had been completed in a different way for the design of a continuous SMC. The limitations of the Continuous SMC is some extent removed using the DTSMC approach[33] The paper is organized as follows, the section II includes the description of electromechanical system with mathematical model while section III focuses on the integral sliding surface. Further part of the paper is organized in following manner. The nest section describes the system for transformation of the system with lower order and higher order into the general second order system models. section III introduces the design of sliding surface and derives overall control law, whereas section IV provides a typical examples for continuous and discrete SMC. The typical controllers are compared to the proposed controller to test its control capabilities and usefulness in a closed loop. Section V presents conclusions and future directions for work.

2. Description of Systems

In general case, second order system is represented as

$$\frac{Y(s)}{U(s)} = \frac{K\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} = \frac{C_n}{s^2 + A_n s + B_n} \tag{1}$$

where, ζ is damping factor, ω_n is natural frequency of oscillation of system, and K is gain of system. Then the given system is required to translate in second order system given by the above Eq. 1. Let us discuss the case of system with low order and in subsequent subsection the case of higher order systems be also considered.

2.1. First order plus delay time systems

The first order plus delay time (FOPDT) model of a system is considered as

$$\frac{Y(s)}{U(s)} = \frac{ke^{-t_d s}}{\tau s + 1} \tag{2}$$

where, the term τ represents time constant, t_d represents time delay, and k represents steady-state gain. As the time delays become too small in comparison with time constant τ, then a system model may become modified by approximation as [7]:

$$\frac{Y(s)}{U(s)} = \frac{k}{(\tau s + 1)(t_d s + 1)} = \frac{C_n}{s^2 + A_n s + B_n} \tag{3}$$

Here in above case, the Taylor series approximation in case of time delay $e^{-t_d s} = 1/(t_d s + 1)$ is used. As this is common in the control theory to use Taylor series approximation for the delay time during the design of control system [5].

2.2. Higher order plus delay time systems

Now transfer function model of higher order plus delay time system is considered as,

$$G_P^1(s) = \frac{b_0}{s^q + a_1^1 s^{q-1} + a_2^1 s^{q-2} + ... + a_q^1} e^{-t_d s}, \tag{4}$$

where, a_j^1 $(j = 1, 2, \cdots, q)$ are constant coefficients of the polynomial. The delay time term $e^{-t_d s}$ is replaced by the first order Taylor approximation with $1/(1 + t_d s)$. After approximation, the transfer function in equation (4) can be written as

$$G_p(s) = \frac{b}{s^n + a_1 s^{n-1} + a_2 s^{n-2} + ... + a_n}, \tag{5}$$

where a_j $(j = 0, 1, 2, \cdots, n)$ represents the constant coefficients. The conversion of any high order system model by first order plus dead time model by approximation is a regular practice. As a matter of fact, all the qualities of higher order process are included in the FOPDT model, but it is sufficient to provide an explanation to the effective dead time, overall time constant, and process gain of system of this type [28]. There are three unknown parameters are needed to create a reasonable FOPDT model to be approximate, namely τ, t_d and k should be determined steady-state gain. Let the transfer function of lower model is denoted by

$$l(s) = \frac{Y(s)}{U(s)} = \frac{ke^{-t_d s}}{\tau s + 1}, \tag{6}$$

and for higher order it is denoted by $h(s) = G_p(s)$. In the literature, the higher order and lower order models at certain places tried to fit the Nyquist plots, but it was unsuccessful [29].

$$\begin{aligned} l(0) &= h(0) \\ |l(j\omega_c)| &= |h(j\omega_c)| \\ \angle l(j\omega_c) &= \angle h(j\omega_c) \end{aligned} \tag{7}$$

where, ω_c represents phase crossover frequency. As a result, the FOPDT model parameters may be determined with the help of [28],

$$\begin{aligned} k &= h(0) \\ \tau &= \frac{\sqrt{(\frac{h(0)}{|h(j\omega_c|})^2 - 1}}{\omega_c} \\ t_d &= \frac{\pi - tan^{-1}(\tau\omega_c)}{\omega_c} \end{aligned} \tag{8}$$

Now from Eq. 3 by getting the above three values of constant parameters, it is easy to obtain the specified structure.

3. Sliding Mode Control Approaches

3.1. Continuous SMC

For continuous SMC, the sliding surface for PID controller with first order filter is defined by:

$$\sigma(t) = \left[K_p + \frac{K_i}{s} + sK_d\right]^{n-1} \Psi(E(s)) \tag{9}$$

where $\Psi(E(s))$ is the Laplace domain tracking error filter, $\Psi(E(s)) = 1/(\lambda s + 1)E(s)$ and 'n' is the order of system. In this, terms K_p, K_i K_d and λ are the parameters used for tuning the controller, these supports in defining the sliding surface $\sigma(t)$ and determined by designer. The sliding surface can be used to determine the how well the system perform. Designing a control law has the purpose of guaranteeing the output of plant response $y(t)$ equal to the set value of reference $r(t)$ for the remaining time, which means the value of error and derivatives of all errors must be equal to zero. In SMC law, the main purpose is to reduce the error signal $e(t)$ to move towards the defined sliding surface also it must stay along with it towards origin. By putting the value of $\Psi(E(s)) = 1/(\lambda s + 1)E(s)$ in Eq. (9), results in

$$\sigma(t) = \frac{1}{\lambda s + 1} K_p E(s) + \frac{K_i}{s(\lambda s + 1)} E(s) + \frac{1}{\lambda s + 1} K_d s E(s) \tag{10}$$

. The transfer function of model is second order, means the term $n = 2$.

The tracking error, in mathematical way may be represented by the equation

$$e(t) = r(t) - y(t) \tag{11}$$

. where, reference input is represented by $r(t)$, $e(t)$ represents error signal, and plant output is represented by $y(t)$. The Second Derivative of above Eq. 11 is

$$\ddot{e}(t) = \ddot{r}(t) - \ddot{y}(t) \tag{12}$$

Generally, from Eq. 3, $\ddot{y}(t) = -A_n\dot{y}(t) - B_n y(t) + C_n u(t) + D(t, u(t))$.
Substituting value of $\ddot{y}(t) = -A_n\dot{y}(t) - B_n y(t) + C_n u(t) + D(t, u(t))$ into the Eq. 12, therefore

$$\ddot{e}(t) = \ddot{r}(t) - [-A_n\dot{y}(t) - B_n y(t) + C_n u(t) + D(t, u(t))] \tag{13}$$

$$\ddot{e}(t) = \ddot{r}(t) + A_n\dot{y}(t) + B_n y(t) - C_n u(t) - D(t, u(t)) \tag{14}$$

The sliding surface second-order derivative which is taken from Eq. 10 is determined with multiplication on both side of equation by $'s(\lambda s + 1)'$. Hence, Eq. 10 may get modified as

$$s(\lambda s + 1)\sigma(t) = sK_p E(s) + K_i E(s) + s^2 K_d E(s) \tag{15}$$

. By modifying above Eq. 15 in the time domain and represented as

$$\ddot{\sigma}(t) = \frac{K_p}{\lambda}\dot{e}(t) + \frac{K_i}{\lambda}e(t) + \frac{K_d}{\lambda}\ddot{e}(t) - \frac{\sigma(\dot{t})}{\lambda} \tag{16}$$

. In view of the Eq. 13, we know that, $\ddot{e}(t) = \ddot{r}(t) + A_n\dot{y}(t) + B_n y(t) - C_n u(t) - D(t, u(t))$. Put this in 16, now it is written as,

$$\ddot{\sigma}(t) = \frac{K_p}{\lambda}\dot{e}(t) + \frac{K_i}{\lambda}e(t) + \frac{K_d}{\lambda}[\ddot{r}(t) + A_n\dot{y}(t) + B_n y(t) - C_n u(t) - D(t, u(t))] - \frac{\sigma(\dot{t})}{\lambda} \tag{17}$$

. When condition $\sigma(t)$=$\dot{\sigma}(t)$ and $\ddot{\sigma}(t) = 0$ with $u(t) = u_{eq}(t)$ is determined, then controller algorithm designed in the form of second-order SMC is primarily established by the equivalent control concept. The control of a system at its nominal parameters is achieved by equivalent control, if $D(t, u(t)) = 0$, given by the steps :
Step 1
As $\ddot{\sigma}(t) = 0$, put in Eq. 17

$$\frac{K_p}{\lambda}\dot{e}(t) + \frac{K_i}{\lambda}e(t) + \frac{K_d}{\lambda}[\ddot{r}(t) + A_n\dot{y}(t) + B_n y(t) - C_n u(t)] - \frac{\sigma(\dot{t})}{\lambda} = 0, \tag{18}$$

. Step 2
Replace u by u_{eq} in Eq. 18

$$\frac{K_p}{\lambda}\dot{e}(t) + \frac{K_i}{\lambda}e(t) + \frac{K_d}{\lambda}[\ddot{r}(t) + A_n\dot{y}(t) + B_n y(t) - C_n u_{eq}(t)] - \frac{\sigma(\dot{t})}{\lambda} = 0. \tag{19}$$

Step 3
Obtain u_{eq} from above Eq. 19

$$u_{eq}(t) = \frac{1}{K_d C_n}(K_p\dot{e}(t) + K_i e(t) + K_d\ddot{r}(t) + K_d A_n\dot{y}(t) + K_d B_n y(t)) + \frac{1}{K_d C_n}(-\frac{K_p}{\lambda}e^{-\frac{t}{\lambda}}e(t) - K_i e(t) + K_i e^{-\frac{t}{\lambda}}e(t) - \frac{K_d}{\lambda}e^{-\frac{t}{\lambda}}\dot{e}(t)). \tag{20}$$

The above value is named equivalent controller. The form of input control to the conventional SMC is:

$$u(t) = u_{eq}(t) + u_{sw}(t) \tag{21}$$

Now we take the switching control, here three switching controls are taken as represented by

$$u_{sw}(t) = k_{sw} r^2(t)\tilde{e}(t) sgn\left(\frac{k_{sf}}{\tilde{e}(t)}\dot{\sigma}(t)\right) + \frac{1}{K_d C_n} sgn(\sigma(t)) \tag{22}$$

where the term k_{sw} is a positive gain employed for reduction of high frequency oscillations known as chattering, by preserving the tracking efficiency, and considering that $r(t) \neq 0$ the setpoint and $\tilde{e}(t)$ is the corrected error given by:

$$\tilde{e}(t) = \epsilon_1 sgn(e(t)) \qquad if|e(t)| \leq \epsilon_1 \tag{23}$$

and

$$\tilde{e}(t) = e(t)) \qquad if|e(t)| \geq \epsilon_1 \tag{24}$$

where, ϵ_1 is a number with small positive value used for avoiding the situation of zero division. At the time os starting, when $t = 0$, the amount of error present in the switching control gain is maximum, so the switching control law provides the maximum control signal. As time approaches infinity, the error value tends to zero. This means that $lim_{t\to\infty} u_{sw}(t) \cong 0$. Depending on the uncertainty of a given time or the error due to external disturbance of the load, the amount of switching control increases and converges to the setpoint more quickly. As the sliding surface represents a functional variable of error signal, condition $\sigma(t) = \dot{\sigma}(t) = 0$ is determined by slight variations near zero, if the error value tends to zero.

3.2. Discrete SMC

The design of the DSMC required to satisfy the stability condition for the reaching phase and sliding phase as same like the continuous SMC given in the section (III). The concept of the reaching condition [25] ,

$$s(t)s\dot{(t)} \leq 0, i.e. \tag{25}$$

$$| s(k+1) |<| s(k) |$$

apply the Lyapunov stability criteria for ideal condition of sliding mode [32]

$$\nu\dot{(t)} < 0, \tag{26}$$

where

$$\nu(t)(t) = \frac{1}{2}s^2(t) \tag{27}$$

which may be written in discrete time as

$$\nu(t)(k+1) - \nu(t)(k) < 0, \tag{28}$$

where

$$\nu(t)(k) = \frac{1}{2}s^2(k) \tag{29}$$

Let us consider the continuous time model of the system represented in the discrete-time model as represented by:

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) + \delta(k) \\ y(k) &= Cx(k) \end{aligned} \tag{30}$$

By defining a state error vector with the equation

$$e(k) = x(k) - y(k) \tag{31}$$

where $e(k)$ is the error signal, and $x(k) = \Re^n$ is the vector of state variables, $u(k) \in \Re$ is the vector input control signal and $y(k) \in \Re$ is the scalar output signal of the system. A, B and C are representing constant value matrices with proper dimensions. The DSMC approach involved in designing the controller have the following steps:

- Determination of a switching function $s(x)$ in such a way that the sliding mode on switching surface $s(x) = 0$ becomes stable.
- Determination of a control law

$$u(k) = \begin{cases} 1, & \text{when } s(k) > 0 \\ -1, & \text{when } s(k) \leq 0 \end{cases} \tag{32}$$

4. Simulation Examples

Example 1: Simulation of sliding mode control is conducted for a brushless DC motor. Results show the successfulness of the controller. The controller is differentiated with existing sliding mode controllers present in literature. For simulation the *Mathworks*^{TM} MATLAB 2019a is used. This paper uses a flat BLDC motor of Maxon's EC 45 with diameter of Φ 45 mm, 30 Watt from Maxon motors [30]. Mathematical models use the parameters that are obtained from the Motor's datasheet as well as othr relevant information. For LDC motors, the mathematical model uses the parameters available in the datasheet [30].

$$G(s) = \frac{1/K_g}{\tau_m \tau_e s^2 + \tau_m s + 1}$$

where K_g, τ_m and τ_e are the constants and required to be determined.

The term τ_e is determined using the relation

$$\tau_e = \frac{L}{3R} = \frac{0.560 \times 10^{-3}}{3 \times 1.10}.$$

Thus,

$$\tau_e = 151.56 \times 10^{-6}$$

The term τ_m is determined using the relation

$$\tau_m = \frac{3R_\phi J}{K_g K_t} = 0.0171$$

where K_e is

$$K_e = \frac{3R_\phi J}{\tau_m K_t} = 0.0763$$

Hence, the DC motor model is represented by transfer function form is

$$G(s) = \frac{13.11}{155.56 \times 0.0171 \times 10^{-6} s^2 + 0.0171 s + 1}$$

or

$$G(s) = \frac{82620}{s^2 + 269.7s + 6302} = \frac{C_n}{1 + A_n + B_n}.$$

The various parameters defined for the controller of proposed here and Furat & Eker [24] are taken as: ksw=200; ksf=0.025; Kp=12; Ki=0.001; Kd=0.0024; with $\lambda = 0.9$; as filter parameter for suggested method. Fig. 1,Fig. 2 and Fig. 3 respectively reveals the output, input and sliding surface responses of the suggested SMC and other considered controllers. Looking at the output response, Furat & Eker provided controller and the controllers implemented here showed speedy and reasonably acceptable response, instead the slow response given by Camacho-2000 and

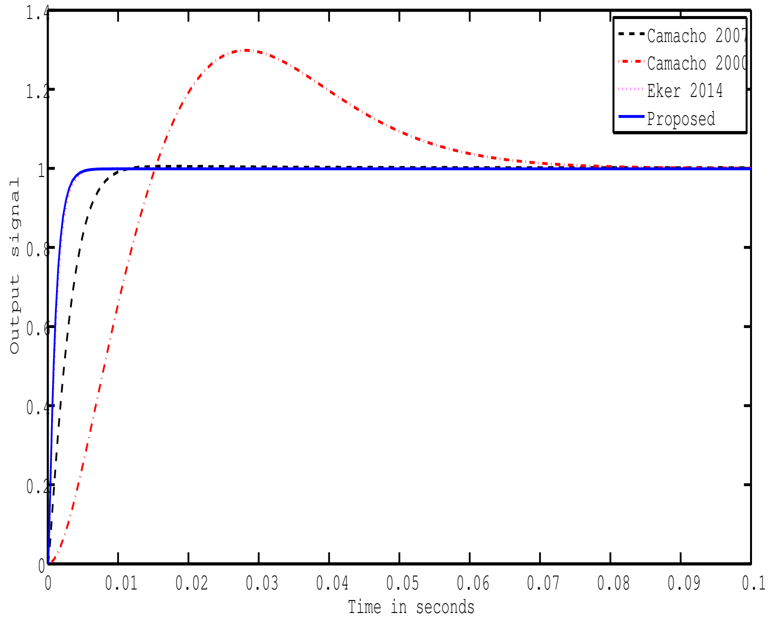

Figure 1: *Output Responses*

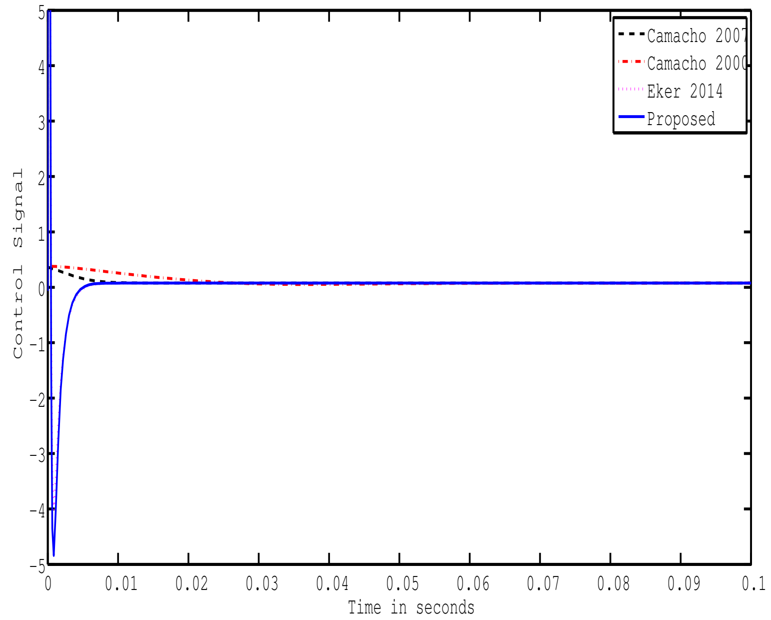

Figure 2: *Input Responses*

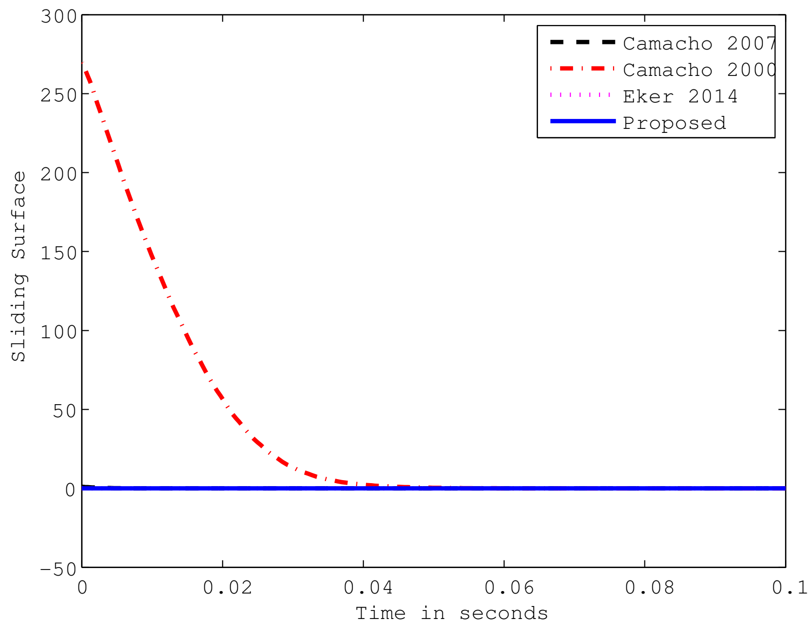

Figure 3: *Error Responses*

Camacho-2007. The suggested response by Camacho-2000 shows high overshoot and unsuitable for applications of electromechanical systems in speed control of the DC motor. The proposed controller provides the smooth response and the stable sliding surface.

At the time $t = 0.05s$, to check the stability and behaviour of all controllers, the output disturbance $d = 0.2r$ is inserted in the system. The controller responses of the controllers are shown in Fig. 4. From the Fig. 4 shows that, controllers provided by Camacho-2000 and Camacho-2007 are not suitable due to poor performance. The controller proposed in this paper provides comparable and preferable performance characteristics.

Example 2: The repeated pole systems are well studied in the literature and are used for design of controller in higher order systems [29].

$$G_p(s) = \frac{1}{(s+1)^5}$$

Using the technique given in section II, the FOPDT parameters of the system are $k = 1$, $\tau = 3.7540$ and $t_d = 2.6566$. The second order model with Taylor approxiamtion for delay time is,

$$\frac{Y(s)}{U(s)} = \frac{0.1003}{s^2 + 0.6428s + 0.1003}$$

4.1. Simulation example of DSMC

Consider the higher order transfer function given in Example 2 reduced in to the third order approximation and represented in state space form [29]

$$G_p(s) = \frac{1}{(s+1)^5}$$

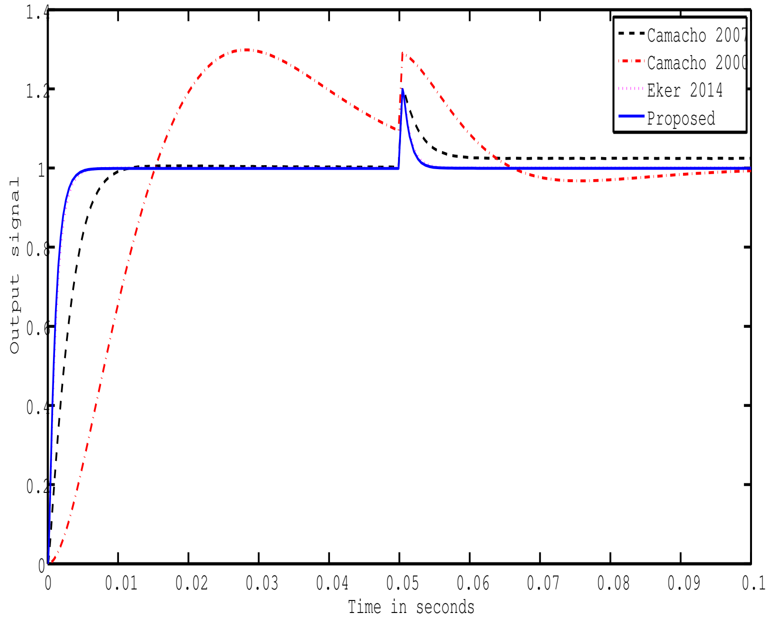

Figure 4: *Output Responses under 20% external disturbance*

An equation in state space can be derived by matched pole-zero method with selected sampling interval of $T_[s] = 0.1s$ and may be given as

$$A = \begin{bmatrix} -1.5630 & -1.0140 & -0.2375 \\ 1.0000 & 0 & 0 \\ 0 & 1.0000 & 0 \end{bmatrix}, B = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix},$$

$$C = \begin{bmatrix} 0.0896 \\ -0.1608 \\ 0.2406 \end{bmatrix}$$

and D=[0].

The parameters used for the prevalent controller Khandekar et.al. , Weibing Gao et.al. & our previous work [31, 32, 33] are: In simulation of [31] switching gain $alpha = 0.4$, $K_t = 1$ and the controller gain matrix $ct =$ [-5.3630 -1.1215 -0.3097]. In simulation of [32] switching gain $alpha = 0.8$, $K_t = 0.8$ and the controller gain matrix $ct =$ [-3.3630 -0.1215 -0.3097]. In simulation of [33] switching gain $alpha = 0.6$, $K_t = 0.8$ and the controller gain matrix $ct =$ [-1.3630 -0.1215 -0.3097]. The performances of DSMC [33] and other controllers are shown in Fig. 5 and Fig. 6 respectively in relation to the output responses and input responses. From these figures, it is observed that the output responses of the controller given by DSMC in [33] controllers gives fast and satisfactory response. It is also observed that the responses are more oscillatory for DSMC of prevalent controllers.

5. Conclusion

According to the results, the integral SMC performs better than the conventional SMC and PID controller in terms of output response. The output response of the integral SMC had no overshoot,faster rise time, and a faster settling time in magnitude. Traditional SMC and PID controllers are unable achieve needs of precise control requirements, resulting in large percentage overshoots and settling times are required for system. The second order integral SMC gives superior performance compared to the conventional SMC or traditional PID controller like

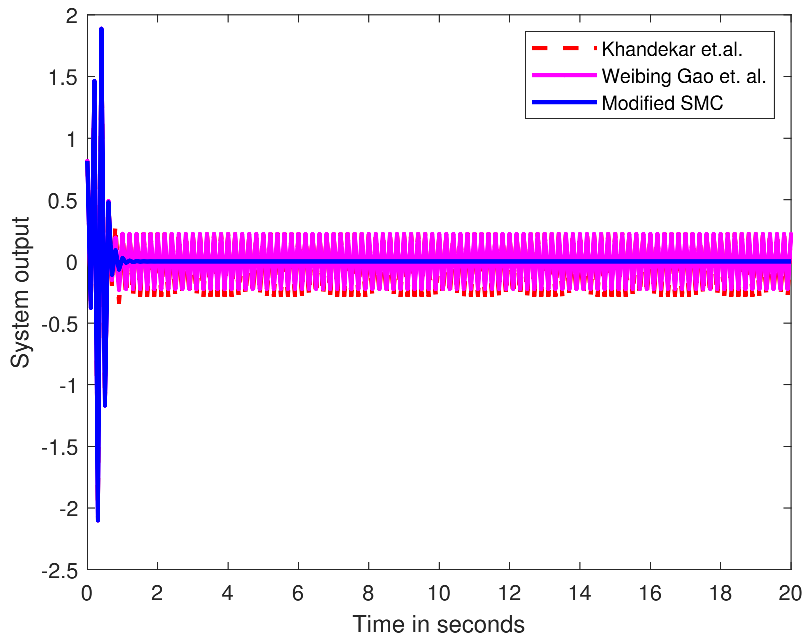

Figure 5: *System output.*

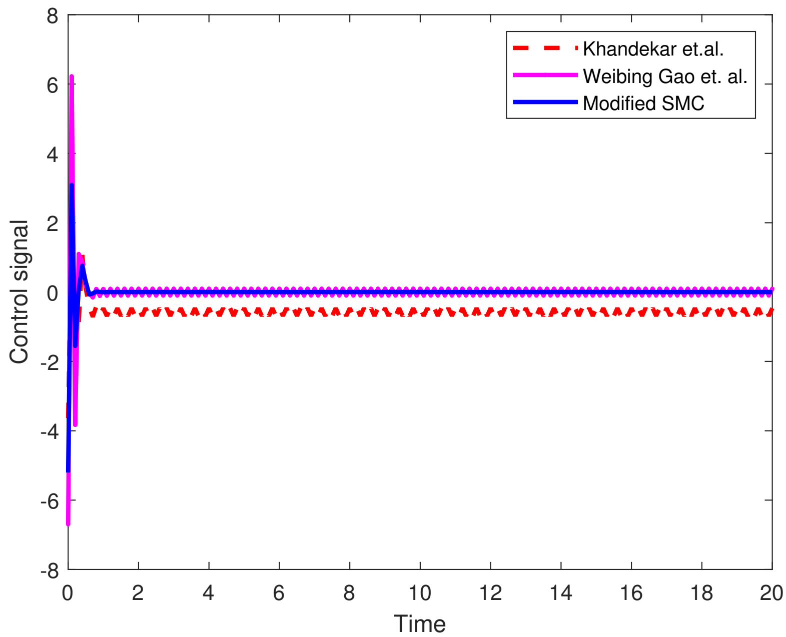

Figure 6: *Control signals*

reducing the overshoot exist in speed, also minimising the rise time and settling time of the system response. Based on the results of simulation, second order integral SMC compared to both conventional SMC techniques gives improved results under nominal parameter or system with uncertainties in the parameters. However, the results obtained for the nominal parameters are better than the results obtained for the system under parametric uncertainties. The conventional SMC simulation results are preferable when the system is at its nominal parameters,but are not acceptable for systems with parametric uncertainty. The second order integral SMC is suitable for systems with uncertain parameters that cannot ne estimated or measured. In case of external disturbance the proposed controller will be useful. Selecting the right sliding surface is critical in the approach to SMC design, also selecting a sliding sirface can significantly reduce the chattering phenomenon, but with an extra work it can be eliminated. The results can be compared to other second order Integral sliding surfaces or by using different control laws. The control approach used in this work is restricted to second order integral SMC, conventional SMC and PID controller, but other control approaches such as higher order SMC, predictive SMC can also be implemented. This work may be further moved forward for the systems with higher than 10% parametric variation with uncertainty in the modification of the control law. This discussed study may be further worked with the applications in real time by designing an experimental setup and DC drive interfacing accessories.

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