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Speed control of PMSM system using improved reaching law based sliding mode control and disturbance observer technique

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Abstract

In this paper, improvement of transient response of the permanent-magnet synchronous motor (PMSM) subjected to different level of load disturbances and parametric uncertainties and unmodeled dynamics are studied using improved reaching law sliding mode control (IRLSMC) and disturbance observer techniques. Proposed scheme is tested under different load conditions and parametric uncertainties. The results of proposed reaching law are compared with other techniques to prove the effectiveness of proposed scheme. Simulation results show the efficacy of proposed control approach.

Keywords

Permanent magnet synchronous motor (PMSM), Sliding-mode control (SMC), improved reaching law sliding mode control.

1. Introduction

In the field of control system, classical proportional integral (PI) control technique is still popular control strategy to control speed of permanent-magnet synchronous motor (PMSM) system, due to its simple construction and ease of implementation [1]. Where the performance of conventional controller is depends on the system parameters. It is designed based on the assumptions that system parameters are constant and not changing as time passes. In the real system, all system parameters are changed due to many reasons such as loading, ageing effect and non-linear coulomb friction [2]. In a conventional sliding-mode controller (SMC), a filter and an additional position compensation of the rotor loop are used to reduce the chattering problem commonly found in the literature [3, 4, 5, 6].

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Currently, a saturation function is used widely for the SMC as a switching function. The robustness of SMC can be guaranteed by the selection of large switching control gain, while the large switching gain leads to the chattering phenomenon, which can excite high-frequency unmodeled dynamics. In order to solve the aforementioned problem reaching law is proposed.

There are two types of ac motors: the induction motor (IM) and the permanent-magnet (PM) synchronous motor (PMSM) [7], [8]. The PMSM is very popular in AC motor applications since it is useful for various levels of speed controls. While the IM has a simple structure and is easy to control. However, IM is not as efficient as the PMSM considered in terms of dynamic response and load characteristics. In order to improve the transient performance characteristics and load compensation novel techniques are studied in this paper. First, conventional SMC is described briefly. The reaching law recently developed is described to compare the results with proposed reaching law. Proposed reaching law improves the reaching time of the system. Due to algebraic combination of linear, saturation and terminal function, one can reduce the reaching time with more number of variable combinations. The results of PI controller are compared with conventional SMC. The performance of proposed scheme is compared with recently reported scheme [9]. Rest of the paper organized as follows: Section 2 describes the problem formulation of the conventional SMC. Conventional reaching law is derived in Section 3, while in section 4 proposed reaching law is derived. The modeling of PMSM system is given in Section 5. Simulation results with conventional controller and proposed scheme are presented in Section 6. Finally the conclusion presented in Section 7.

2. Problem formulation

Sliding mode control (SMC) strategy is become popular nonlinear control technique to control system with external disturbances and uncertainties. When the system is in sliding mode, system states are insensitive to external unmeasureable disturbances and parameter variations, when the control is designed using sliding mode controller. However, conventional

SMC is suffered from chattering due to discontinuous control action. In this paper, switching function is smoothed using saturation function. In this section, the basic SMC methodology is introduced. The SMC framework consists of two crucial steps:

1. Design of sliding surface
2. Design of control such that system trajectory is forced towards the sliding surface, which ensures the system to satisfy the sliding-mode reaching condition that is expressed as follows

$$\sigma\dot{\sigma} < 0 \quad (1)$$

where σ is the sliding variable.

A complete derivation of conventional reaching law based SMC is described in [7]. In order to explain the concept of proposed scheme, basic steps of SMC is described briefly in this section.

Consider a second order non-linear system with external disturbances and non-linearity as follows:

$$\left.\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= a(x) + b(x)u + d(x,u,t) \end{aligned}\right\} \quad (2)$$

where x_1 and x_2 are the states of the systems, u is the control input, $a(x)$ and $b(x)$ are known, smooth function, are system parameters. The disturbance $d(x,u,t)$ consists state, input and time dependent uncertainties and unknown disturbances.

Now define the sliding surface as follows to make both the states to zero from initial conditions. This problem is known as regulatory control problem.

$$\sigma = c_1 x_1 + x_2 \quad (3)$$

where c_1 is the positive constant selected by the designer. It decide the rate at which states goes to zero. When the system is in sliding mode, sliding variable become zero and the system states are insensitive to variations. The states of the system are driven by discontinuous control action.

Now the control is derived to attract the system trajectories into sliding mode. The equal reaching law is given by:

$$\dot{\sigma} = -k\,\mathrm{sgn}(\sigma) \quad (4)$$

In order to derive controller differentiate eq. (3) and substitute the system dynamics of eq. (2) as follows:

$$\dot{\sigma} = c_1\dot{x}_1 + \dot{x}_2 = -k\,\mathrm{sgn}(\sigma) \quad (5)$$

Simplifying the equation further:

$$c_1 x_2 + a(x) + b(x)u + d(x,u,t) = -k\,\mathrm{sgn}(\sigma) \quad (6)$$

In order to stabilize the system control input u can be designed as follows:

$$u = -\frac{1}{b(x)}\left[c_1 x_2 + a(x) + k\,\mathrm{sgn}(\sigma)\right] \quad (7)$$

where *k* is the switching gain to be designed. The switching law is depends on the upper bound of lumped uncertainties. This arises two limitation of conventional SMC as:

1. Discontinuous control leads to chattering in control input and eventually in the system states.
2. In order to design the control input, upper bound of lumped uncertainty is required to be known.

The time required to reach system states entered into sliding mode can be described as follows:

$$t = \frac{\sigma(0)}{k} \quad (8)$$

In eq. (8), it is observed that, the reaching time can be reduced by increasing the switching gain *k*, but it increases the problem of chattering of control input is also increases. In order to resolve this issue, conventional reaching law and proposed reaching law are introduced in the next section.

3. Conventional reaching law based sliding mode control

The novel reaching law based SMC was proposed in [9]. The brief derivation is presented in this section. This reaching law was realized based on the choice of an exponential term that adapts to the variations of the according to the sliding-mode surface and the system states place. This reaching law is given by

$$\dot{\sigma} = -k\,\mathrm{sgn}(\sigma) \quad (9)$$

where the switching gain is given by [9]

$$k = \frac{k_1}{\left[\varepsilon + (1 + 1/|x_1| - \varepsilon)e^{-\delta|\sigma|}\right]} \quad (10)$$

where $k_1>0$, $\delta > 0$ and $0 < \varepsilon < 1$. *are the system states.*

In this technique, one can observe that if $|\sigma|$ increases with the respected to time *t*, the switching gain k converges to the constant value of k_1/ε which is greater than the value of k in the magnitude. This indicates that a faster reaching time can be obtained as compared with the conventional equal reaching law. On the other hand, if $|\sigma|$ decreases, denominator term of the k approaches $1 + 1/|x_1|$, then the k converges to $k_1\ |x_1|\ /\ (1 + |x_1|)$, in which the system state $|x_1|$ gradually decreases to zero under the control input designed in this section. This indicates that when the system trajectory approaches the sliding-mode surface, the k gradually decreases to zero to suppress the chattering as states goes towards the origin. Thus, the controller designed by this reaching law can dynamically adapt to the variations of the sliding-mode surface and system states $|x_1|$ by making the switching gain k vary between k/ε and zero in magnitude.

The reaching time to reach sliding variable is given by:

$$t < \frac{\varepsilon|\sigma(0)|}{k_1} \tag{11}$$

From eq. (11) shows that reaching time can be lower by reducing the value of ε and/ or increasing the magnitude of k_1. In order to reduce the reaching time further by improving the reaching law of the controller further in the next section.

4. Proposed reaching law based sliding mode control

In this section, proposed reaching law is described to improve the transient response and better reaching time as compared to the previously designed reaching law.

$$\dot{\sigma} = -k_s \cdot sat(\sigma) - k_l\sigma - k_t|\sigma|^{\alpha}\operatorname{sgn}(\sigma) \quad (12)$$

Where k_s is the switching function, k_l is the linear gain and k_t is the terminal switching gain to be designed. One can observe that switching function present in the conventional reaching law is replaced with saturation function, which supresses the chattering up to certain extends. The sat function is defined as follow:

$$sat(\sigma) = \begin{cases} \operatorname{sgn}(\sigma), if\,|\sigma| > \varepsilon \\ \sigma/\varepsilon, elsewhere \end{cases} \tag{13}$$

Where ε is the boundary layer constant which decide the smoothing of switching function. The constant $1 < \alpha < 2$ decide the convergence rate of sliding variable when it is more than 1 in the magnitude.

Here, the nature of the different type of function is described in Fig. 1.

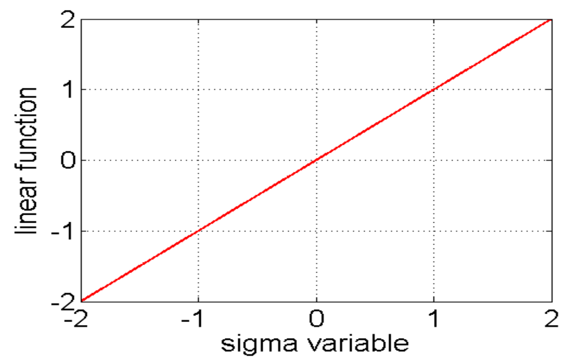

Figure 1: (a) linear function

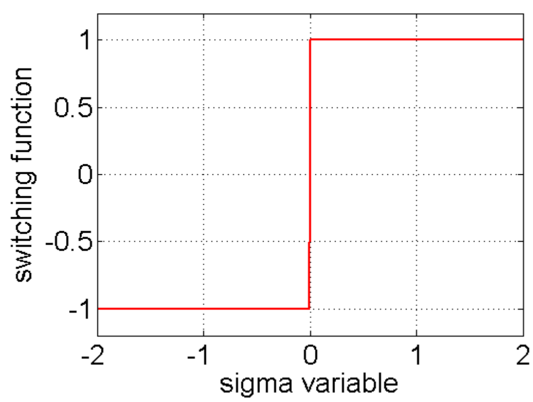

Figure 1: (b) Switching function

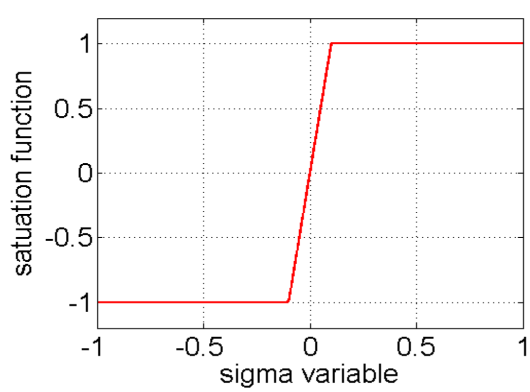

Figure 1: (c) Smooth (saturated) function

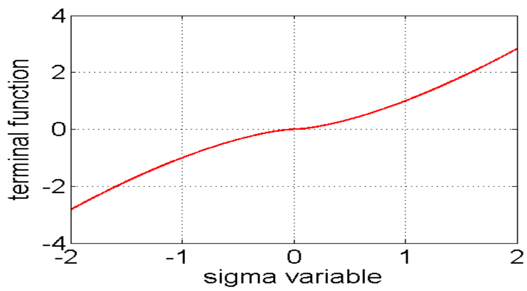

Figure 1: (d) Terminal function

Figure 1: Different function used in the proposed reaching law

One can observe that, linear gain increases or decreases according to sliding variable value. Switching function has {-1, 1} magnitude all over the region based on sliding variable value. While saturation function is combination of linear and switching function. In the linear region, it has very high gain and in other region has constant gain. The terminal function is combination of switching function and power law function gives better response, when σ is higher in magnitude.

The reaching time for a given controller reaching law is given by the following function:

$$t < \frac{\varepsilon|\sigma(0)|}{f(k_l, k_s, k_t, \alpha)} \tag{14}$$

where the function in the denominator of eq. (14) can be selected appropriately to reduce the reaching time of the system. One can observe that proposed reaching law has more flexibilities and more degree of freedom to reduce the reaching time, which is advantageous as compared to other methods mentioned in the literature.

The derivation of disturbance observer dynamics can be found in [9]. Here in order to explain the concept of actual controller design, briefly explained as follows:

$$\sigma = \omega - \omega_{ref} \tag{15}$$

$$\dot{\omega} = a_n i_q + d(t) - c_n \omega \tag{16}$$

The disturbance estimation of lumped disturbance is given by:

$$\dot{\hat{\omega}} = a_n i_q + \hat{d}(t) - c_n \hat{\omega} \tag{17}$$

$$u = \frac{1}{a_n}\left[\dot{\omega}_{ref} + c_n \omega - \hat{d}(t) + k_{eq}\, func(\sigma)\right] \tag{18}$$

where the reaching law is given by:

$$k_{eq} = -k_s \cdot sat(\sigma) - k_l \sigma - k_t |\sigma|^{\alpha} \operatorname{sgn}(\sigma) \tag{19}$$

The estimation of disturbance is given by $\hat{d}(t)$ and the estimation of speed is given by $\hat{\omega}$. The detailed modelling and dynamics of the PMSM system is described in the next section.

5. Modelling of PMSM system

The PMSM system dynamics can be described by the following sets of equations [8, 9]:

$$T_e = \frac{3}{2} p \psi_a i_q \tag{20}$$

$$T_e - T_L = \frac{J}{p}\dot{\omega} + B\omega \tag{21}$$

$$u_d = ri_d - \omega L i_q + L\dot{i}_d \tag{22}$$

$$u_q = ri_d + \omega L i_d + \omega \psi_a + L\dot{i}_q \tag{23}$$

where u_d and u_q is the control input represents the d and q axis voltages across the stator winding respectively. The d and q axis phase current represented by i_d and i_q respectively. The stator resistance and inductance represented by r and L respectively. Here, we have assumed that inductance and resistances almost equal in all phases of motor stator winding. The electrical torque is represented by T_e, the mechanical toque represented by load toque T_l. p is the number of poles of the motor magnets. The mechanical inertia is represented by J and viscous friction is represented by the symbol B. The electrical angular speed is given by ω. The flux linkage of the permanent is given by ψ_a.

Table 1: Parameters of PMSM system

Parameter (Symbol)	**Value**	**Unit**
Stator Inductance (L)	11.5	*mH*
Phase resistance (r)	3.5	Ω
Viscous friction (B)	0.00001	*N.m.s/rad*
Number of Pole pairs (P)	3	
Rotational Inertia (J)	0.00044	$Kg.m^2$
Flux Linkage of the permanent magnets (ψ_a)	0.107	*Wb*

In order to simulate the PMSM system performance in Simulink, parameters are considered as per Table 1.

6. Simulation results and discussion

In this section, proposed method performance is compared with the other methods found in the literature. Initially, the performance of equal reaching law based sliding mode controller is compared with the conventional PI controller. In order to show fair comparison of proposed method and best reaching law designed till date are compared. The reaching law designed in Section 3 and proposed reaching law performance is compared with simulation example.

Fig. 2 shows the comparative plot of speed of PMSM system using conventional PI controller and equal reaching law based SMC. One can noticed that the overshoot in SMC is zero as compared with PI controller and has less settling time. One can improve the response PI controller response by tuning it with other methods. Here the purpose of comparison is to show the qualitative performance comparison.

Fig. 3 shows the phase current plot using PI controller, from initial current condition it goes to steady state value after some time.Fig. 4 shows the plot of sigma variable using conventional SMC. It is defined as difference of actual and desired velocity, it has desired value of 500 RPM and initial value of actual velocity is zero, is starts from 500 RPM.

In Fig. (5) phase current i_d and i_q is plotted, due to switching function, it has chattering in the steady state. Same chattering can be observed in the desired current i_q^* also.

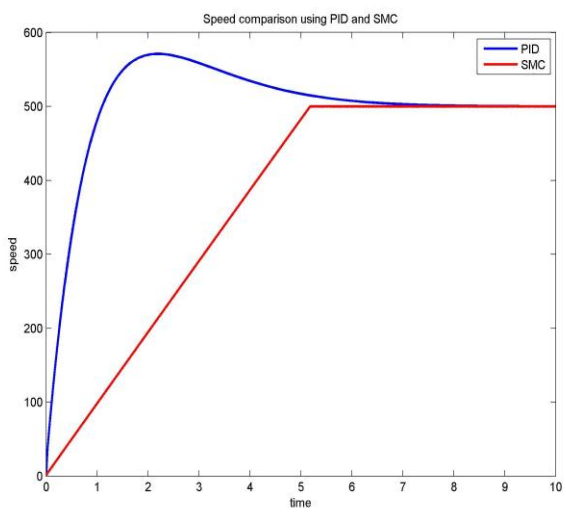

Figure 2: Comparative plot of speed of PMSM using PID controller and Conventional SMC

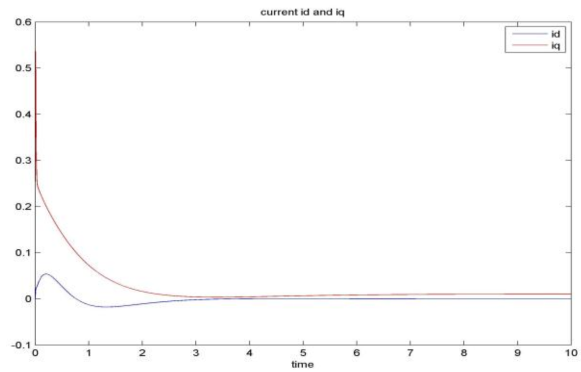

Figure 3: Plot of phase currents I_q and I_d using PI controller

Fig. 7 shows the Simulink implementation block diagram of proposed scheme. After initialization of all parameters, simulink model is executed to test controller.The comparative result of proposed scheme with the reaching law proposed in [9] is shown in Fig. 8. Time history of other parameters with proposed scheme is presented in Fig. 9-12.

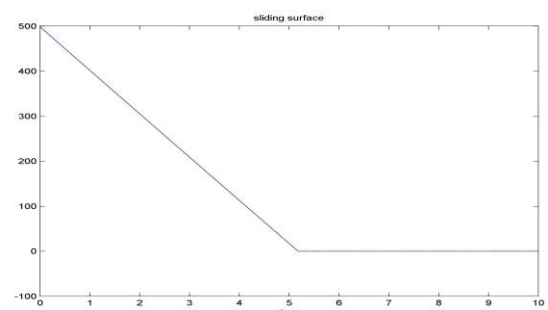

Figure 4: Plot of sliding surface variable σ using conventional SM controller

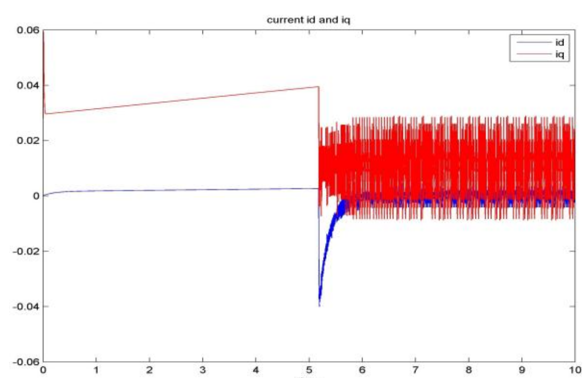

Figure 5: Plot of phase currents I_q and I_d using conventional SM controller

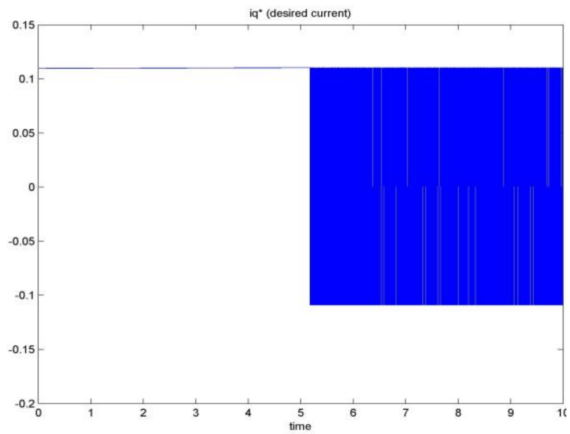

Figure 6: Plot of desired current generated using SM controller

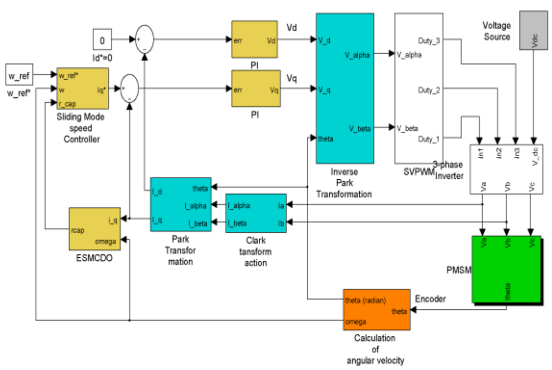

Figure 7: Simulink diagram implementation of proposed scheme

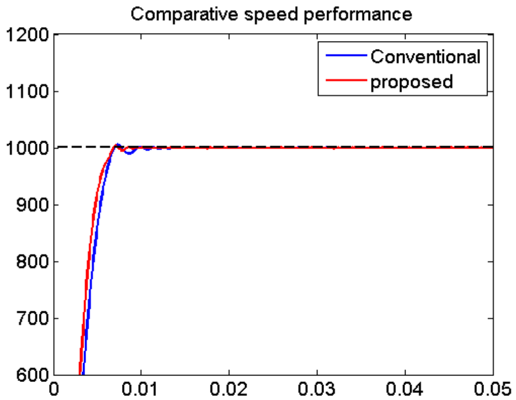

Figure 8: Plot of speed of PMSM using conventional and proposed reaching law with SM controller

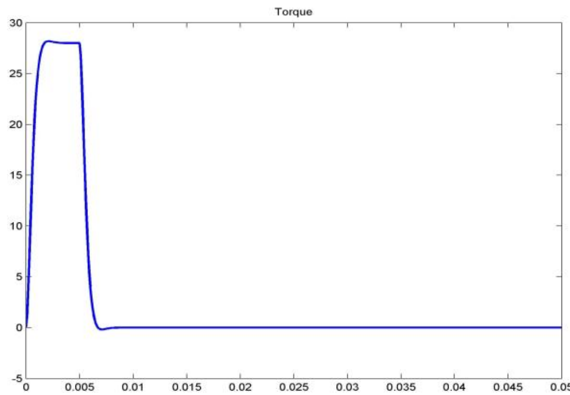

Figure 9: Plot of electrical toque of PMSM using proposed reaching law based SM controller

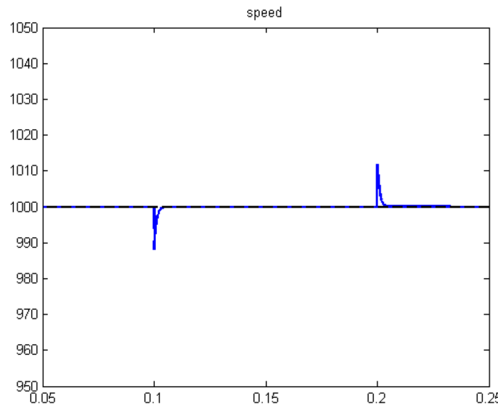

Figure 10: zoom view of speed response of PMSM using proposed reaching law SM controller

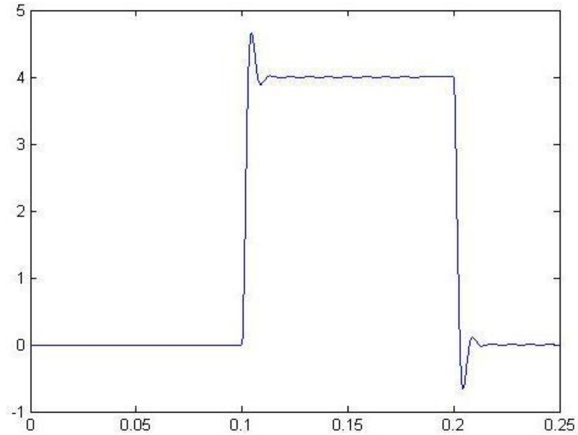

Figure 11: Plot of load disturbance using proposed reaching law SM controller

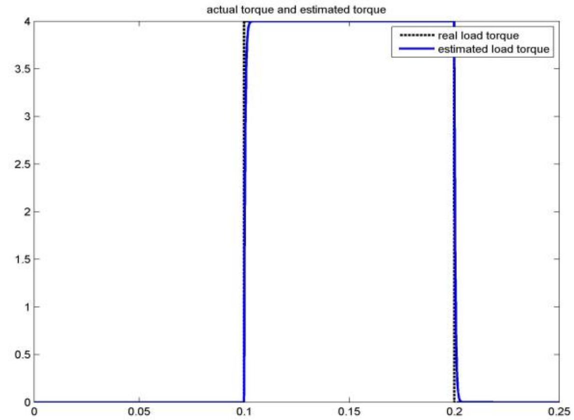

Figure 12: Plot of actual load torque and estimated load toque using disturbance observer technique

7. Conclusion

In this paper, improved reaching law based sliding mode controller is presented. The review of conventional, recently designed and proposed reaching law schemes are studied briefly. The simulation result of proposed scheme is compared in Simulink. Simulation results show that proposed scheme has better transient response and lower reaching time.

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