

SIMULATION OF BLDC MOTOR CONTROL USING SLIDING MODE CONTROL TECHNIQUE

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ABSTRACT

Mostly, Brushless DC motors have been used in various industrial and domestic applications because of its advantages like simple structure, large torque, long use time, good speed regulation. Generally the BLDCM systems have uncertain and nonlinear characteristics which degrade performance of controllers. Based on these reasons, Sliding Mode Control (SMC) is one of the popular control strategies to deal with the nonlinear uncertain system. In This work implemented a SMC scheme for effective speed tracking by obtaining ripple free torque through the inner loop current control for a BLDCM. The second order mathematical model of the BLDCM is developed for simulation purposes. Two first order sliding controllers based on the exponential reaching law algorithm are developed for the inner loop current control and also for outer loop speed control of the drive. Performance of the speed tracking is then compared with a classical PI (Proportional and Integral) controller implemented for the speed loop and the advantages of the sliding mode scheme related with reduction of steady state error, settling time, percentage overshoot and disturbance rejection. This scheme is robust against the parameters variations. This work has been carried out with simulation studies using MATLAB2009.

KEYWORDS: BLDC Motor, Sliding mode control, Exponential reaching Law, PI(Proportional plus Integral) controller.

I. INTRODUCTION

BLDC motors, also called Permanent Magnet DC Synchronous motors. These motors are one of the motor types that have more rapidly gained popularity, mainly because of their better characteristics and performance [1]. The Brushless DC motors are widely used in many industrial and traction applications because of its overwhelming advantages like high efficiency, high torque, low maintenance, less noise and low volume. The BLDC motor can act as an alternative for traditional motors like Brushed DC motor, induction motor, switched reluctance motors etc [1]. The brushless DC motor is a synchronous electric motor that from a modeling perspective and looks exactly like a DC motor because motor having a linear relationship between current and torque as well as voltage and rpm. It is an electronically controlled commutation system. In earlier days the controlling system of BLDC motor adopted hall sensor signals to drive the motor. But when disturbance on the hall sensor exists, the misbehavior of the main circuit prompts and motor action unsteady and reliability of the whole controlling system is greatly reduced as well as the cost of controller is increased. In recent years, some of these developments like Proportional Integral (PI) [3] controllers have been implemented for the speed control of BLDC motors. BLDC motors can be controlled by used various advanced control theories like the optimal and adaptive strategies. Neural network control [4] has also been used to control these motors but its performance under load disturbances and parameter uncertainty due to the non linearity cannot give expected results.

Sliding mode control is a technique that originated in Soviet literature, in the early 1950's initiated by S. V. Emelyanov, with advantages like order reduction, disturbance rejection and invariance to parametric variations have now become very popular for designing of robust system performance. Speed and current control of different motor drives [7] is amongst many of its other areas of application. In this paper design of SMC for inner current control loop and outer speed loop by using

exponential reaching-law based on the sigmoid function is proposed and by applying the proposed technique the stability of the entire loop and also the smoothness of the converging process of the system are better than those obtained by using the classical PI controller. These two first order SMC loop design by using mathematical modeling of BLDC motor.. The sliding surface can be reached quickly and the system chattering can be reduced at the same time. Also SMC is used for reducing faster settling time, disturbance on parameter variation .Simulation results obtained using the developed control scheme is carried out on MATLAB/SIMULINK software and shows that the proposed method is feasible and more effective.

II. BLDC MOTOR AND ITS MATHEMATICAL MODELLING

2.1. BLDC Motor

Now a days electric vehicles and micro electric motor cars in the market mostly adopt BLDC motor. This motor is also called Permanent Magnet DC Synchronous motors. And also this motor is a synchronous electric motor that from a modeling perspective and looks exactly like a DC motor and having a linear relationship between current and torque as well as voltage and rpm. The control of BLDC motors can be done in sensor or sensorless mode, but to reduce overall cost of actuating devices, sensorless control techniques are normally used. The advantage of sensorless BLDC motor control is that the sensing part can be omitted and overall costs can be considerably reduced. Because of their high power density, reliability, efficiency, maintenance free nature and silent operation, permanent magnet (PM) motors have been widely used in a variety of applications in industrial automation, computers, aerospace, military (gun turrets drives for combat vehicles) [2], automotive (hybrid vehicles) and household products. However, the PMBLDC motors are inherently electronically controlled and require rotor position information for proper commutation of currents in its stator windings. It is not desirable to use the position sensors for applications where reliability is of almost importance because a sensor failure may cause instability in the control system. A PM brushless drive that does not require position sensors but only electrical measurements is called a sensorless drive BLDC motor is widely used because of its advantages like high efficiency, high power density, torque, fast response and low inertia. Fast dynamic response, higher steady precision and stronger anti-interference capability is required in many applications for the motor speed regulation system. These motor also has better speed vs. torque characteristics, High dynamic response, long operating life, Noiseless operation, high speed ranges and Low maintenance. The permanent magnet brushless motor has a permanent magnet rotor and the stator windings are wound such that the back emf is trapezoidal. It requires rectangular shaped stator phase currents to produce constant torque. The trapezoidal back emf implies that the mutual inductance between the stator and rotor is non-sinusoidal. The model of BLDC motor is similar to that of a DC motor. Only here the presence of an electronic commutator causes the state trajectory to switch between different models. Here the model of a BLDC similar to that of a DC motor is developed. By incorporating the presence of an electronic commutator the developed model can be used as a BLDC drive model [3,4,5]. The below Figure 1.shows the equivalent circuit of DC motor [10,13],

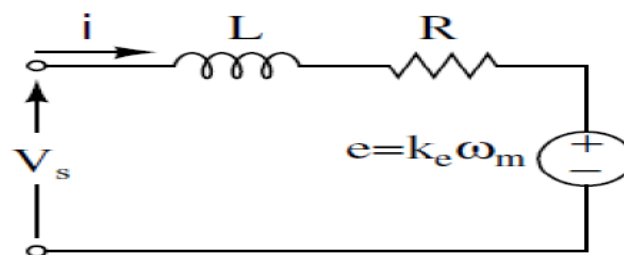


Figure1: Equivalent circuit of DC motor.

The parameters of the motor model used in this paper are illustrated in Table1

Table1: Parameters Of The Motor

Sr. No.	Symbol	Description	Value
1.	B	Friction coefficient	10-2Kg/ms
2.	J	Moment of Inertia	3.99×10^{-5} Kgm ² /s ²
3.	Kb	Back emf constant	0.105volts/rad/sec
4.	Kt	Torque constant	0.0980N - m/Amp
5.	L	Inductance	1.1×10^{-3} Henry
6.	P	No. of poles	4
7.	R	Resistance per phase	0.525Ohms

2.2. Mathematical Modelling

The differential equation governing the electrical part of the model can be written as,

$$v = iR + L \frac{di}{dt} + E \quad (1)$$

where, V=DC voltage applied in Volts.

L=Inductance of the windings in Henry.

R=Resistance of the windings in Ohms.

E = Kb ω =Back emf of the motor.

Kb =Back emf constant in Volts/ rad/ sec.

ω =Speed in rad/ sec.

The above equation (1) can be written as,

$$\frac{di}{dt} = \frac{1}{L}(-E - iR + V) \quad (2)$$

Where, I = Current in Amp.

V =Voltage as input.

E=Disturbance as input.

The relation between torque and speed can be obtained by the following differential equation as,

$$T = \frac{d\omega}{dt} + B\omega + TL. \quad (3)$$

Where,

T=Torque in Newton -meter.

J=Moment of inertia in Kg/ ms.

TL= Disturbance input.

B=Coefficient of friction in Kg/ms.

The above equation (3) can be written as

$$\frac{d\omega}{dt} = \frac{1}{J}(-B\omega + T + TL) \quad (4)$$

Where,

Electrical torque T = Kt ω ,

Kt=Torque Constant.

We know that, $\omega = d\theta/dt$,

Define the state, let $x_1 = i$, $x_2 = \omega$ and $x_3 = \theta$,

The above equation can be written as in state space form as below,

$$\begin{pmatrix} \dot{i} \\ \dot{\omega} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} -\frac{R}{L} & -\frac{Kb}{L} & 0 \\ \frac{Kt}{J} & -\frac{B}{J} & 0 \\ 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} i \\ \omega \\ \theta \end{pmatrix} + \begin{pmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{J} \\ 0 & 0 \end{pmatrix} \begin{pmatrix} V \\ TL \end{pmatrix} \quad (5)$$

and output equation is,

$$\begin{pmatrix} i \\ \omega \\ \theta \\ T \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ Kt & 0 & 0 \end{pmatrix} \begin{pmatrix} i \\ \omega \\ \theta \end{pmatrix} \quad (6)$$

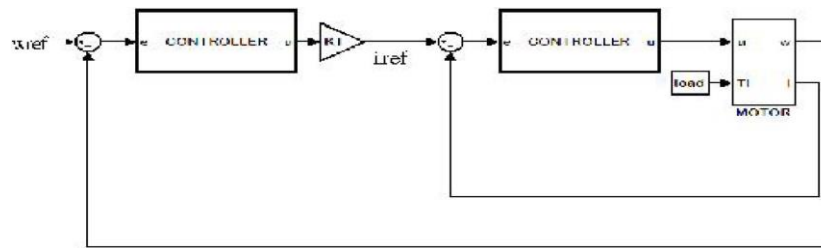


Figure 2. Block diagram of the control loop without controller when ω_{ref} , i_{ref} is the reference speed and current. In this diagram the outer loop is to control the speed whereas the inner loop is used to control the current.

III. CONCEPT OF SLIDING MODE CONTROLLER

In this control technique the concept of reaching law [1] algorithm emphasizing on the benefits of exponential reaching law [2] are used to control the inner current loop and outer speed loop of the BLDC motor. Sliding mode control is a typical non linear control technique [1], that modifies the system performance by continuous switching of the controlled variable according to the current status of the known system state and thereby causes the trajectory to move on a predefined sliding surface.

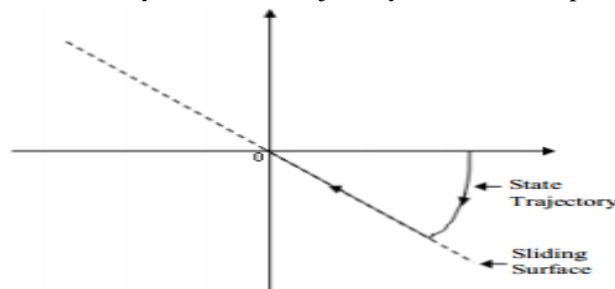


Figure3: Phase Portrait of a sliding motion

Figure (3) represents the phase trajectory of a sliding mode representing two modes of the system. In the first part, the trajectory starting from anywhere on the phase plane moves towards the sliding surface and reaches the surface in finite time. This is known as reaching, hitting, or non-sliding phase and the system is sensitive to parameter variations and disturbance rejection in this part of the phase trajectory. The second part is the sliding phase in which the state trajectory moves to the origin along the sliding surface and the state never leave the sliding surface. During this period, the system is defined by the equation of the sliding surface and thus it is independent of the system parameters and external disturbances [7].

Sliding mode design involves two major tasks:

- The selection of a stable sliding surface [2] in state space on which the state trajectory must ultimately lie in.
- Designing a suitable control law that makes this sliding surface attractive for the state trajectory to reach it in finite time.

Sliding surface can be either linear or nonlinear. For simplicity, only a linear sliding surface is used. If the origin of the coordinate axes is taken as the stable equilibrium then the ultimate objective is to force the trajectory onto the sliding surface, "S" and then it should move towards the origin. The idea behind SMC is to define a surface along which the process can slide to its desired final value. The structure of the controller is intentionally altered as its state crosses the surface in accordance with a prescribed control law. Thus, the first step in SMC is to define the sliding surface $s(t)$. $s(t)$ is chosen to represent a desired global behavior for instance stability and tracking performance. The objective of control is to ensure that the controlled variable be equal to its reference value at all times means that error $e(t)$ and its derivatives must be zero. Once the reference value is reached, it indicates that sliding surface $s(t)$ reaches a constant value. To maintain $s(t)$ at this constant value, means that error $e(t)$ is zero at all times; it is desired to make that,

$$\dot{s} = \frac{ds(t)}{dt} = \frac{d(\text{constant})}{dt} = 0 \tag{7}$$

Once the sliding surface has been selected, attention must be turned to design of the control law that drives the controlled variable to its reference value and satisfies above equation. The SMC control law, u , consists of two additive parts; a continuous part, u_{eq} , and a discontinuous part, u_{sw} . That is ,

$$u = u_{eq} + u_{sw} \tag{8}$$

Slotine proposed a form of general equation to determine the sliding surface [3] which ensures the convergence of a variable towards its desired value as:

$$S = \left(\frac{d}{dt} + \alpha\right)^{n-1} e \tag{9}$$

Where, n is the system order, e is the tracking error signal and α is a positive constant that determine the bandwidth of the system.

For the controlling purpose of two loops we consider and two sliding surfaces are taken as,

$$S_1 = e_1 = i_{ref} - i \tag{10}$$

$$\text{And } S_2 = e_2 = \omega_{ref} - \omega \tag{11}$$

Where

i_{ref} = Reference current

and ω_{ref} = Reference speed.

Having chosen the sliding surface at this stage, the next step would be to choose the control law (u) that will allow the error to reach the sliding surface. To do so, the control law should be designed in such a way that the following condition, also named reaching condition, is met:

$$s\dot{s} < 0 \tag{12}$$

In order to satisfy this condition, exponential reaching law [1,2] technique is adopted. The general representation of the exponential reaching law approach is given as,

$$\dot{s} = -\epsilon \text{sgn}(s) - Ks \tag{13}$$

Where K, ϵ are positive constants known as the hitting control gain or parameter, s is the sliding surface, and sgn is the signum function defined as,

$$\text{sign}(s) = \begin{cases} 1 & \text{if } s > 0 \\ -1 & \text{if } s < 0 \end{cases} \tag{14}$$

The discontinuous control law described by Equations presents high robustness, insensitive to parameter fluctuations and disturbances. However, using a sign function often causes chattering phenomenon.

IV. CONTROL ALGORITHM

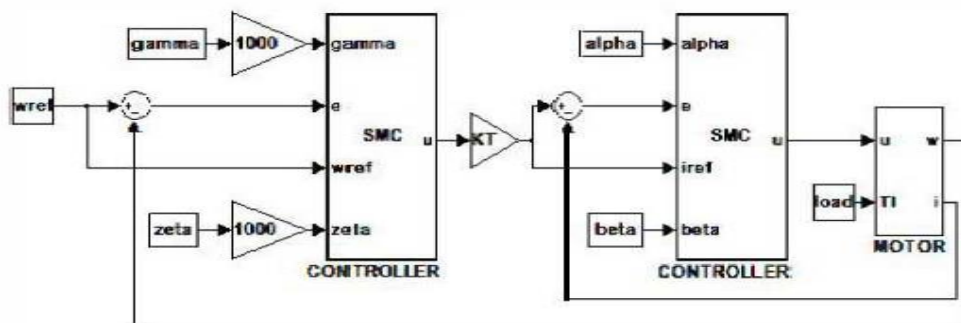


Figure.4. Block Diagram of BLDC Motor with Sliding Mode Controller.

The block diagram of the sliding mode controller is shown in Fig.4 which represents two controllers. In those one controller is used for current loop and other is used for speed loop of the BLDC motor. In the outer loop, the speed error of the motor is minimized by continuous varying of positive constants γ and ζ , thereby reaching the desired speed of the motor. The output from the speed controller is fed as input to the other controller which is designed for current control. In the inner loop, the current error of the motor is minimized by continuous varying of positive constants α and β , thereby causing the motor to run at required current.

By employing the exponential reaching law [5] approach the sliding mode controllers can be designed. For inner current loop, the sliding mode controller, S_1 can be obtained as,

$$V = L[\alpha \text{sgn}(s_1) + \beta s_1 + di/dt] + E + (i - e_1)R \tag{15}$$

α, β are constants, e_1 is the current error signal; S_1 is the SMC controller for current loop. Similarly for outer speed loop, the sliding mode controller, S_2 obtained as,

$$T = J \left[\gamma \text{sgn}(s_2) + \zeta s_2 + \frac{d\omega}{dt} \right] + Tl + (\dot{\omega} - e_2)B \tag{16}$$

Where, γ, ζ are constants, e_2 is the speed error signal S_2 is the SMC controller for speed loop.

V. SIMULATION RESULTS

To validate the control techniques as described simulation were carried out on a BLDC motor drive system by using MATLAB/SIMULINK software.

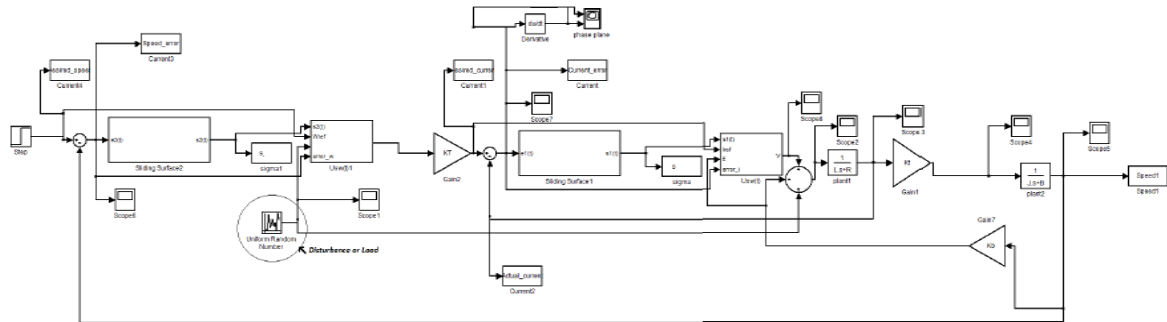


Figure5. Total Simulink Diagram

a. No load Condition with Variation in ζ :

Table2. Variation of ζ at no load condition

Parameter	Symbol	$\zeta = 250$	$\zeta = 350$	$\zeta = 450$
Error(Speed)	$e\omega$	0.0059%	0.0025%	0.0021%
Error(Current)	ec	0.1331%	0.0062%	0.0023%
Current settling time(sec)	tc	0.02	0.023	0.024
Speed settling time(sec)	$t\omega$	0.02	0.021	0.02
%Overshoot(speed)	Mp	0%	0	0

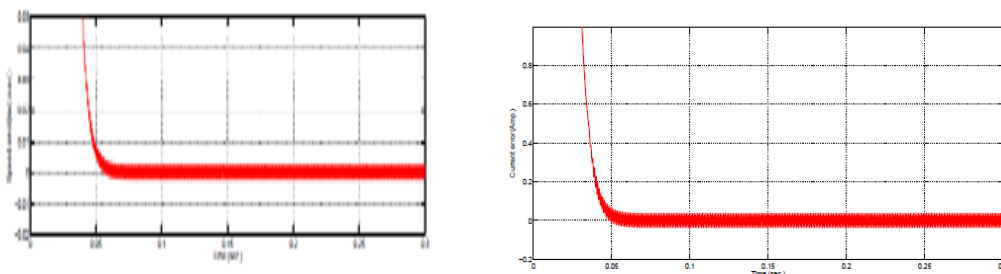


Figure6.Speed-errorand Current control of BLDC Motor under No Load Condition

b. No load condition with variation in β :

Table3. Variation of β at no load condition

Parameter	Symbol	$\beta = 10$	$\beta = 100$	$\beta = 1000$
Error(Speed)	$e\omega$	0.0010%	0.0059%	0.0653%
Error(Current)	ec	0.2258%	0.1331%	0.058%
Current settling time(sec)	tc	0.029	0.011	0.009

Speed settling time(sec)	$t\omega$	0.036	0.021	0.0038
%Overshoot(speed)	Mp	0%	0	0

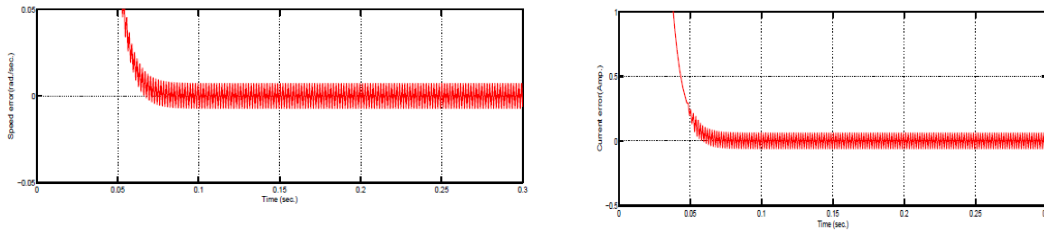


Figure7.Speed-error and current error of BLDC Motor under No Load Condition

c. No load condition with variation in α :

Table4.Variation of α at no load condition

Parameter	Symbol	$\alpha = 1$	$\alpha = 30$	$\alpha = 50$
Error(Speed)	$e\omega$	0.0039%	0.0024%	0.0059%
Error(Current)	ec	0.0569%	0.3297%	0.1983%
Current settling time(sec)	tc	0.032	0.023	0.009
Speed settling time(sec)	$t\omega$	0.039	0.030	0.026
%Overshoot(speed)	Mp	0%	0	0

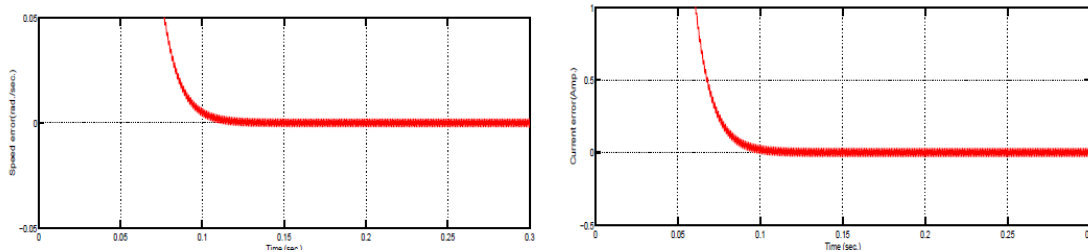


Figure8.Speed-error and current error of BLDC Motor under No Load Condition

d. No load condition with variation in γ :

Table5.Variation of γ at no load condition

Parameter	Symbol	$\gamma = 1$	$\gamma = 50$	$\gamma = 100$
Error(Speed)	$e\omega$	0.0066%	0.0017%	0.0023%
Error(Current)	ec	0.1137%	0.3224%	0.3291%
Current settling time(sec)	tc	0.018	0.019	0.0191
Speed settling time(sec)	$t\omega$	0.027	0.0265	0.026
%Overshoot(speed)	Mp	0%	0	0

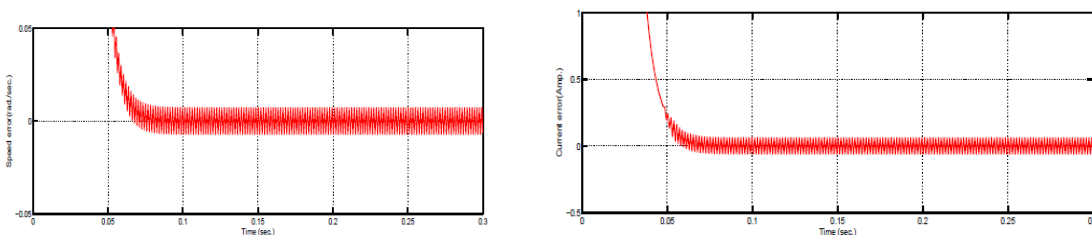


Figure9: Speed-error and current error of BLDC Motor under No Load Condition

5.1 Simulation result using PI controller in speed control loop

In this case, it assumed that the reference speed is 100 rad/sec and there is no load condition. The parameters of the PI controller is: $K_p = 1$ and $K_i = 14.28$. The speeds of the motor with SMC and PI controller are shown as,

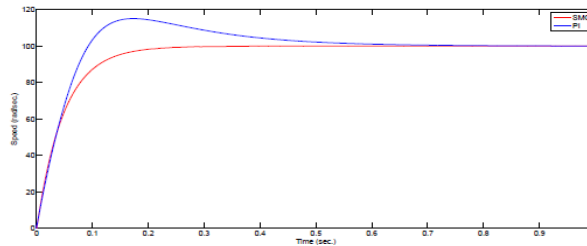


Figure10. Speed of BLDC Motor with SMC and PI Controller.

Table6. Simulation Results with SMC and PI Controller

Parameter	Symbol	smc	pi1
Error(Speed)	$e\omega$	0.0248%	0.0646%
Error(Current)	ec	0.1403%	0.0297%
Current settling time(sec)	t_c	0.185	0.6
Speed settling time(sec)	t_ω	0.195	0.52
%Overshoot(speed)	M_p	0%	15

VI. CONCLUSION AND FUTURE WORK

6.1 Conclusion

This work is intended to use the exponential Reaching law for successful design of SMC for BLDC motors using mathematical modeling. Also it is intended to compare the two Controllers namely, Proportional-Integral (PI) controller and sliding mode controller (SMC) for the speed control of a brushless DC motor. It is observed that,

- SMC provides important advantages over the traditional PI controller like limiting the overshoot in speed, thus the starting current overshoot can be reduced.
- From the simulation results, both techniques give required result. However, simulation results show that the sliding mode controller realized a good dynamic behavior of the motor with a rapid rise time and settling time, and had better performance than the PI controller related to reduction in steady state error, faster settling time, smaller overshoot in the speed response and much better disturbance rejection capabilities against parameter variations and external load torque.

6.2 Remarks

1. In SMC, it is important to select the suitable sliding surface. By selection of sliding surface, chattering phenomenon can be reduced significantly, however further work can be done to eliminate it.
2. The results can be compared with selection different sliding surfaces or using various control laws.
3. The control strategy used in this work is limited to SMC and PI controller, however different control strategies such as adaptive, predictive can be implemented to compare the results with SMC.

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