# Modified Sliding Mode Observer for Position and Speed Estimations in Brushless DC Motor

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*Abstract*— **This paper reports an adaptive gain sliding mode observer for Brushless DC (BLDC) motor for large variations in speed. BLDC motor based on sliding mode observer exhibits multiple zero crossing in back EMF which leads to commutation problem at low speed. In this paper a modified sliding mode observer incorporating the speed component in the estimation of back EMF is proposed. It is found that after incorporating speed component in the back EMF observer gain, multiple zero at low speeds and phase shift at higher speeds are eliminated. Detailed simulation results are carried out to verify the effectiveness of the proposed scheme.**

***Keywords*— BLDC; back EMF; sliding mode observer**

## I. Introduction

Permanent magnet BLDC motor with the trapezoidal back electromotive force has got the momentum in industrial applications due to their high efficiency and reliability. Usually, these motors outweigh the normal dc motor with their special feature of being brushless which reduces the losses caused due to brushes. The other reasons for the vast usage of BLDC motors in domestic applications are long lifetime, reduced noise and overall reduction of electromagnetic interference. To control the BLDC motor effectively, the rotor position signals are obtained from the Hall position sensors. Mostly three Hall Effect sensors are used to determine the position as it is only required to know the position of commutation points. However, installing those Hall Effect sensors in the motor will make the structure of the motor complex and reduce its reliability. Hence, sensor less control of the BLDC drive has become the trend of researchers these days.

Several methods for obtaining rotor position and speed have been reported in the literature [1-6]. These methods are based on: using the back EMF of the motor [1-2];detection of the conducting state of freewheeling diodes in the unexcited phase [3]**;** and the stator third harmonic voltage components [4]. However, the mentioned strategies work well only over a limited range of speed. The estimation of the instantaneous rotor position is proposed in [5], the Extended Kalman Filter (EKF) is used to estimate the instantaneous rotor position and speed of the BLDC motor, but the speed estimation accuracy is decreased, particularly at low speeds. Unfortunately, this stochastic observer has some inherent disadvantages, such as the computational burden and the absence of design and tuning criteria. Indirectly back EMF is being estimated through sliding mode observer [6-11] even though, the sliding mode observer is an valuable alternative with respect to measurement noise and parametric uncertainty of the system, a single back EMF observer gain value does not suit for wide range of speeds.

In the conventional method, a single observer gain value is selected for estimating back EMF which suits well only for particular range of speeds for which the observer gain is deigned. The invariable observer gain produces multiple zero crossing for low speeds and a phase delay for large range of speeds. In the proposed method, value of the observer gain varies in accordance with the variation of speed to match the estimated back EMF with actual.

The paper is organized as follows. In section II, BLDC motor model is presented. In section III, proposed modified sliding mode observer for BLDC motor is designed and simulated results are presented in section IV.

## II. BLDC MOTOR MODEL

A BLDC motor with trapezoidal back electromotive force coefficient is taken into consideration. The equivalent circuit of BLDC motor with three phase six switch inverter is shown in Fig.1. The BLDC motor can be modelled using the following equation considering the phases are balanced.

$$\begin{aligned}
\frac{d}{dt}(i_a - i_b) &= \frac{R}{L}(i_a - i_b) - \frac{1}{L}E_{ab} + \frac{1}{L}V_{ab} \\
\frac{d}{dt}(i_b - i_c) &= \frac{R}{L}(i_b - i_c) - \frac{1}{L}E_{bc} + \frac{1}{L}V_{bc} \qquad (1) \\
\frac{d}{dt}(i_c - i_a) &= \frac{R}{L}(i_c - i_a) - \frac{1}{L}E_{ca} + \frac{1}{L}V_{ca}
\end{aligned}$$

where ,($E_{ab}$, $E_{bc}$, $E_{ca}$) are the phase to phase back-EMF, ($V_{ab}$, $V_{bc}$, $V_{ca}$) are line voltages of the inverter and ($i_a$, $i_b$, $i_c$) are the phase currents. If the sampling period is significantly less than the electrical and mechanical time constants then the back EMF value can be assumed to be constant during each sampling period [12] and hence differentiation of the back EMF equals zero. So the equation (1) is written as

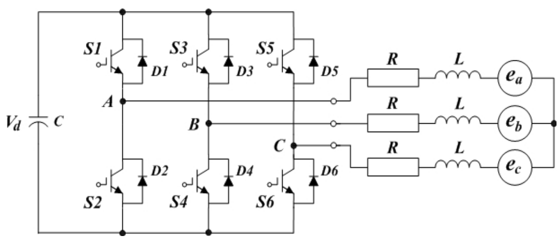



Fig. 1: BLDC motor drive with inverter

$$\frac{d}{dt}(i_a - i_b) = \frac{R}{L}(i_a - i_b) - \frac{1}{L}E_{ab} + \frac{1}{L}V_{ab}$$
$$\frac{d}{dt}(i_a - i_b) = \frac{R}{L}(i_a - i_b) - \frac{1}{L}E_{ab} + \frac{1}{L}V_{ab}$$
$$\frac{d}{dt}E_{ab} = 0 \qquad (2)$$
$$\frac{d}{dt}E_{bc} = 0$$

III. DESIGN OF PROPOSED SLIDING MODE OBSERVER FOR BLDC MOTOR

The system shown in equation (2) mainly depends upon the line currents and line voltages. The modified sliding mode observer is proposed as:

$$\dot{\widehat{x_1}} = -\frac{R}{L}x_1 - \frac{1}{L}\widehat{x_3} + \frac{1}{L}V_{ab} + K_{11}\text{sign}(x_1 - \widehat{x_1})$$

$$\dot{\widehat{x_2}} = -\frac{R}{L}x_2 - \frac{1}{L}\widehat{x_4} + \frac{1}{L}V_{bc} + K_{22}\text{sign}(x_2 - \widehat{x_2})$$

$$\dot{\widehat{x_3}} = \{K_{31} * f(N)\}\text{sign}(x_1 - \widehat{x_1}) \qquad (3)$$

$$\dot{\widehat{x_4}} = \{K_{42} * f(N)\}\text{sign}(x_2 - \widehat{x_2})$$

where, $X_1$ is the line current difference between phases a and b; $X_2$ is the line current difference between phases b and c; $X_3$ is the line back EMF (for line ab); $X_4$ is the line back EMF (for line bc); $K_{11}$ and $K_{22}$ are the line current observer gain ; $K_{31}$ and $K_{42}$ are the back EMF observer gain for lines are selected as mentioned in [6].

Since, the back EMF and the speed of BLDC motor are inter-related with each other, variation of speed must be considered for estimating back EMF and hence function of speed is included in the estimation of back EMF as shown in Fig. 2. The third back EMF is obtained by taking difference between the two. The zero crossing of these back EMF's produce the output as same as that of the Hall Effect sensors which is being used for the position detection of the rotor. Hence, these three outputs after the Zero crossing detector's interpret the information to switch on the switches of the inverter The rotor speed is estimated using the mathematical relation given below from the estimated back EMF.

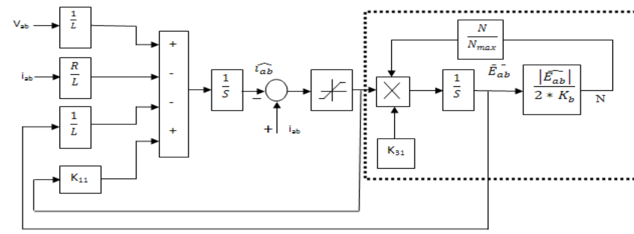



Fig. 2 : Proposed sliding mode observer

Rotor speed = Max of $E_{ab}$ /(2 * back EMF constant)

IV. SIMULATION RESULTS

To evaluate the performance of the proposed sliding mode observer, time domain simulation studies in MATLAB \ SIMULINK environment are presented. The parameters of the motor are : stator resistance=5.25 Ω; stator inductance=20 mH; back EMF constant=0.34 V/rpm; no. of pair of poles= 4; nominal voltage= 500 V. The proposed sliding mode observer is evaluated by considering three different cases: low speed, medium speed and high speed.

CASE 1: Performance of the observer at low speeds

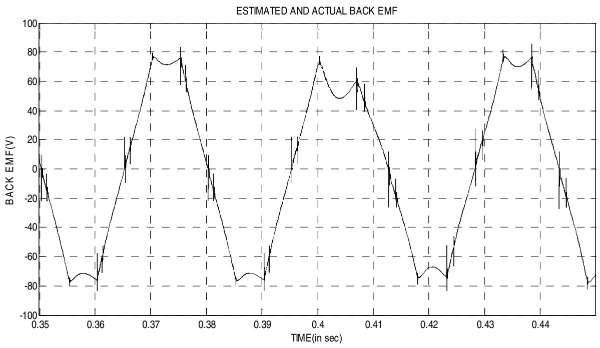
The motor is operated at a speed of 500 rpm. The estimated back EMF and the actual back EMF coincides with each other in both the conventional and the proposed back EMF. However, the conventional method exhibits multiple zero crossing as shown in Fig. 3(a). The multiple zero crossing produces undesired switching instants at the time of zero crossing. The switching instants are shown in Fig. 3(c). These undesirable multiple zero crossings are eliminated by the proposed sliding mode observer and the estimated back EMF perfectly synchronises with the actual back EMF as shown in Fig. 3(b) and (d).

CASE 2: Performance of the observer at medium speeds

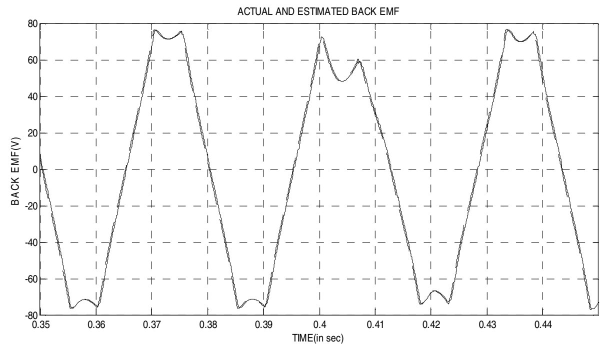
When the motor is operated at a speed of 1500 rpm the conventional method and proposed sliding mode observer does not have any multiple zero crossing. The estimated and actual back EMF of conventional method synchronizes with each other because the designed observer gain suits well for medium range of speeds. The proposed method also works well under this condition which is illustrated in Fig. 4.(a)-(d)

CASE 3: Performance of the observer at high speeds

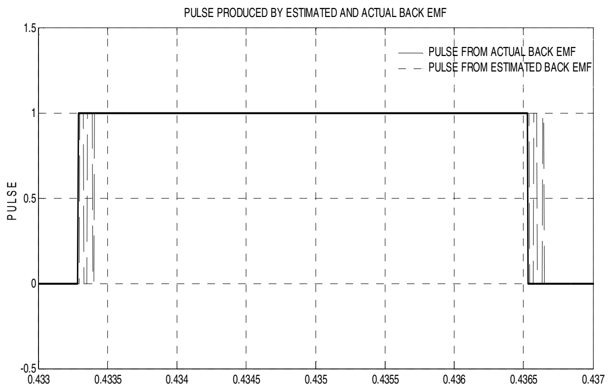
When the motor is operated at a speed of 3000 rpm, the estimated back EMF and actual back EMF does not match with each other as shown in Fig. 5(a) instead they have a phase delay of 20° and this delay increases with increase in speed and reduced gain. Due to this the pulses produced from them also follows the same phase delay as shown in Fig. 5(c). This is eliminated by the proposed method as shown in Fig. 5(b) and 5(d).



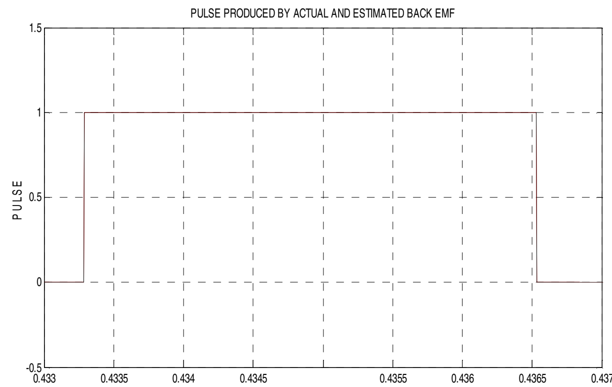

(a)




(b)

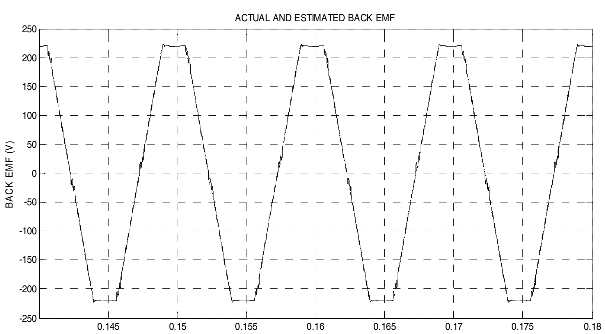



(c)

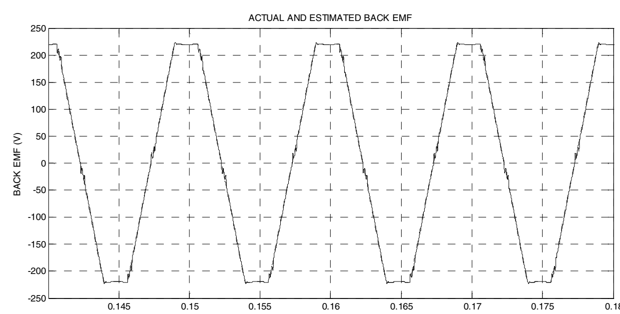



(d)

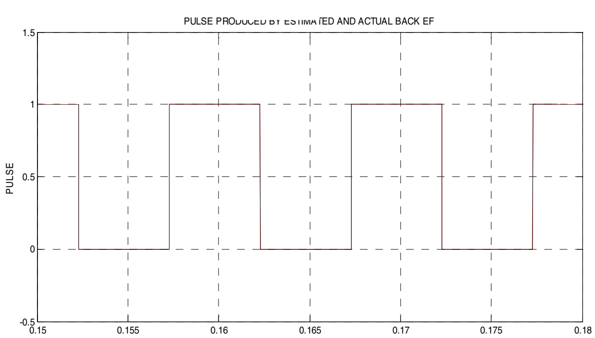
Fig.3 :- Simulation results of the conventional and proposed sliding mode observer for rotor position estimation of BLDC motor at low speed (N=500 rpm): (a) Comparison of actual and estimated back EMF derived from conventional method. (b) Comparison of actual and estimated back EMF derived from proposed method. (c) Switching pulses obtained by conventional method. (d) Switching pulses obtained by proposed method.



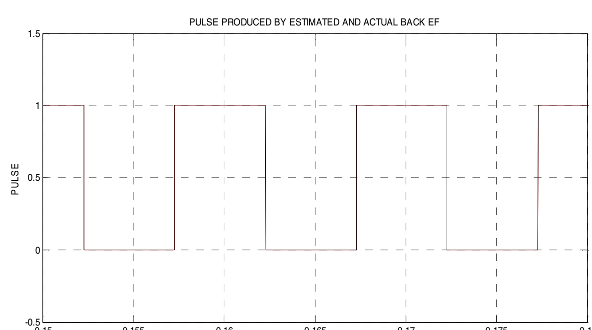

(a)




(b)

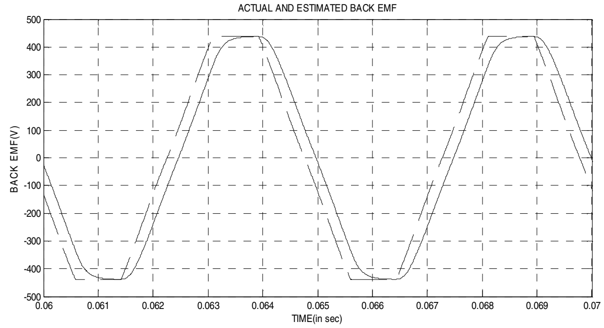



(c)

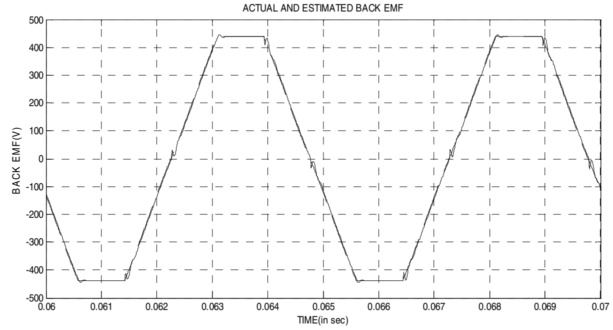



(d)

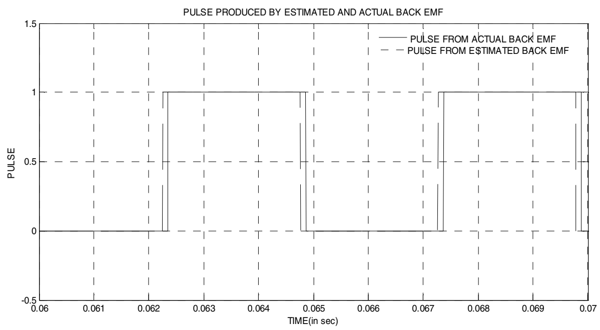
Fig.4.:- Simulation results of the conventional and proposed sliding mode observer for rotor position estimation of BLDC motor at medium speed (N=1500 rpm): (a) Comparison of actual and estimated back EMF derived from conventional method. (b) Comparison of actual and estimated back EMF derived from proposed method. (c) Switching pulses obtained by conventional method. (d) Switching pulses obtained by proposed method.



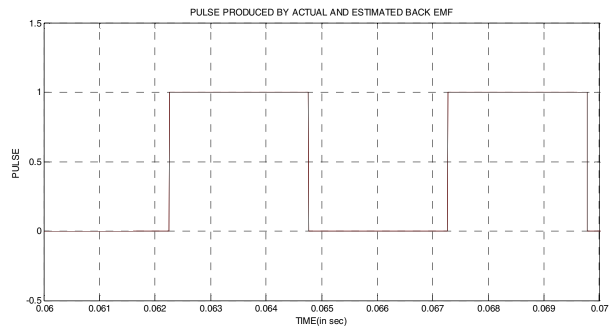

(a)




(b)




(c)




(d)

Fig. 5:- Simulation results of the conventional and proposed sliding mode observer for rotor position estimation of BLDC motor at high speed (N=3000 rpm): (a) Comparison of actual and estimated back EMF derived from conventional method. (b) Comparison of actual and estimated back EMF derived from proposed method. (c) Switching pulses obtained by conventional method. (d) Switching pulses obtained by proposed method.

To synchronise the estimated with actual back EMF, the absolute value of back EMF observer gain must be increased with increase in speed. In the proposed method, the ratio between actual to that of maximum speed is taken and multiplied with the back EMF observer gain. This ratio increases with increase in speed. Hence, the observer gain can be maintained as constant and the speed ratio makes the total gain to increase or decrease according to the variations in speed.

## V. CONCLUSIONS

In this paper, back EMF is estimated indirectly with the help of estimated and actual line currents through modified sliding mode observer. This, back EMF in turn interprets the rotor position through the zero crossing points. Inclusion of speed as a function in the observer gain of sliding mode observer eliminates the multiple zero crossing at low speeds and avoids mismatch between the estimated and actual back EMF at higher speeds. The results obtained from the simulation prove that the modified observer has good convergence for wide range of speeds.

## REFERENCES


[1] R.Becerra, T.Jahns, and M.Ehsani, ‘‘Four Quadrant Sensorless Brushless ECM Drive,” IEEE Applied Power Electronics Conference and Exposition 1991, pp.202-209.

[2] J.Shao, “Direct Back EMF detection method for sensorless Brushless DC (BLDC) Motor drives” M.S. thesis, Dept. Elect. Eng., Virginia Polytechnic institute Virginia, September 2003.

[3] S.Ogasawara and H.Akagi, **“**An Approach to Position Sensorless Drive for Brushlcss dc Motors” IEEE Trans. on Industry Applications, Vo1.27**,** No.5, Sept/ Oct.1991.

[4] J.Moreira, “Indirect Sensing for Rotor Flux Position of Permanent Magnet AC Motors Operating in a Wide Speed Range,” IEEE Industry Application Society Annual Meeting 1994, pp.401-407.

[5] B.Terzic,and M.Jadric, “Design and Implementation of the Extended Kalman Filter for the Speed and Rotor Position Estimation of Brushless DC Motor**”** IEEE Trans, on Industrial Electronics, Vol. 48, No. 6, December 2001.

[6] H.Fakham, M.Djemai, P.Blazevic**,** “Sliding modes observer for position and speed estimations in brushless DC motor (BLDC motor),”IEEE ICIT, Tunisia, 2004.

[7] H. Watanabe, T. Isii, and T. Fujii, “DC-brushless servo system without rotor position and speed sensor,” in Proc. IEEE IECON’87, 1987, pp.228–234.

[8] N. Matsui, “Sensorless operation of brushless DC motor drives,” in Proc. IEEE IECON’93, vol. 2, 1993, pp. 739 744.

[9] T. Furuhashi, S. Sangwongwanich, and S. Okuma, “A position-and-velocity sensorless control for brushless DC motors using an adaptive sliding mode observer,” IEEE Trans. Ind. Electron., vol. 39, pp. 88–95, Feb. 1992.

[10] Y. Fujimoto and A. Kawamura, “Robust servo-system based on two-degree- of-freedom control with sliding mode,” IEEE Trans. Ind. Applicat., vol. 42, pp. 272–280, May/June 1995.

[11] A. Kawamura,H. Itoh, and K. Sakamoto, “Chattering reduction of disturbance observer based sliding mode control,” IEEE Trans. Ind. Electron., vol. 30, pp. 456–561, Apr. 1994.

[12] Bijnan Bandyopadhyay, Fulwani Deepak, and Kyung-Soo Kim. "Sliding mode control using novel sliding surfaces;" Springer, 2009.