Sensorless Speed Control for Brushless DC Motors System Using Sliding-Mode Controller and Observers

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Abstract— **An improved sensorless operation scheme for the Brushless DC motors (BLDC) control system is proposed. A high-speed sliding-mode observer (SMO) for back electromotive force (back-EMF) estimation is employed to obtain the position and speed. A speed control algorithm for the BLDC control systems combining a sliding mode controller with disturbance observer (DOB) is developed to restrain the speed fluctuation caused by abrupt change of load torque. The DOB is used to estimate the load torque and generate a feed-back compensating signal for a controller. Detailed simulation results show that the proposed high-speed SMO could improve the estimation accuracy, and the designed compensating scheme could enhance the robustness against the abrupt load torque change effectively.**

Keywords-sliding mode observer (SMO); sliding mode control (SMC); disturbance observer (DOB); sensorless

I. INTRODUCTION

Brushless DC motor (BLDC) has been widely used in various fields. And, a great deal of attention has been given to the sensorless control of BLDC motor.

On the one hand, a large number of methods have been proposed to obtain or estimate the rotor position and speed, including the extended kalman filter (EKF) [1], artificial neural networks (ANN) [2], model reference adaptive system (MRAS) [3] and sliding mode observer (SMO) [4-6]. SMO is well known for its simple structure and good robustness [4]. For chatting reduction of sliding mode at a high speed, low pass filter and reaching law method are used in the sliding mode observer [4, 5]. For large speed variations, a modified SMO incorporating the speed component in the estimation of back electromotive force (back-EMF) is proposed [6].

On the other hand, in a practical BLDC control system, there are a large number of the disturbances and uncertainties, e.g., parameter variation, friction force, and load disturbance. Large quantities of control techniques have been adopted to improve the performance in systems with varies of disturbances and uncertainties, such as sliding mode control (SMC) technique [7], , robust control technique [8], adaptive control technique [9], intelligent control technique [10], and so on. SMC technique is popular for its good robustness, convenient realization, and the applicability to control with strong nonlinearity and load variation [8, 10]. Moreover, the great robustness of SMC could be achieved by increasing the control gains, while the large gains will lead to the chattering phenomenon at the same time.

To solve the aforementioned problems, a high-speed SMO is employed to estimate the back-EMF. The SMC combining with disturbance observer (DOB) for load torque is adopted to further improve the disturbance rejection performance. In the SMO proposed above, the sigmoid switching function and exponential reaching law are adopted and the gain could be adjusted by the reference velocity. Then, the output of DOB is adopted as the feedforward compensation for the sliding-mode speed controller. Thus, a composite method which combines an SMC part with a feedforward compensation (DOB) and the back-EMF estimation part based on SMO, is developed. Finally, the effectiveness of the proposed scheme was verified by simulation results.

II. BLDC MODEL AND SENSORLESS OPERATION

A. BLDC Model

In order to deduce the third back-EMF between the two phases and under the assumption that the system is balanced, the BLDC simplified model is as follows [6]:

$$\begin{cases} \dfrac{d(I_a-I_b)}{dt} = -\dfrac{\alpha}{\beta}(I_a-I_b) - \dfrac{1}{\beta}E_{ab} + \dfrac{1}{\beta}U_{ab} \\ \dfrac{d(I_b-I_c)}{dt} = -\dfrac{\alpha}{\beta}(I_b-I_c) - \dfrac{1}{\beta}E_{bc} + \dfrac{1}{\beta}U_{bc} \\ \dfrac{dE_{ab}}{dt} = 0 \\ \dfrac{dE_{bc}}{dt} = 0 \end{cases} . \tag{1}$$

Where, $\alpha = R, \beta = L - M$, U , I , E are the phase voltages, phase currents, phase back-EMF of three-phase windings respectively, and the subscripts a, b and c

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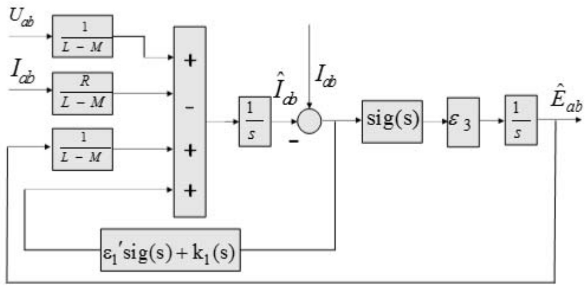


Figure 1. Structure of the proposed SMO.

correspond to the three phases respectively, L is stator self- inductance, M is mutual inductance between each two phase, R is the stator resistance, E_{ab}, E_{bc} are the phase-to-phase back-EMF, U_{ab}, U_{bc} are line voltages of the inverter.

Electrical torque is represented as

$$Te = k_t I \ . \tag{2}$$

Considering the electrical torque as well as the load torque T_L, the equation of motion of the rotor is shown as follows.

$$T_e - T_L = J\frac{dw}{dt}. \tag{3}$$

Where k_t is torque coefficient; w is the mechanical rotational speed; J is the rotational inertia of the motor; $\frac{dw}{dt}$ is the angular acceleration of the rotor.

B. Traditional Sliding mode observer

Note that the system (1) mainly depends upon the line currents and line voltages. The traditional sliding mode observer with a sign switching function and a normal speed reaching law could be easily described as follows:

$$\begin{cases} \dot{\hat{x}}_1 = -\alpha_1 x_1 - \alpha_2 \hat{x}_3 + \alpha_2 U_{ab} + \varepsilon_1 \operatorname{sgn}(x_1 - \hat{x}_1) \\ \dot{\hat{x}}_2 = -\alpha_1 x_2 - \alpha_2 \hat{x}_4 + \alpha_2 U_{bc} + \varepsilon_2 \operatorname{sgn}(x_2 - \hat{x}_2) \\ \dot{\hat{x}}_3 = \varepsilon_3 \operatorname{sgn}(x_1 - \hat{x}_1) \\ \dot{\hat{x}}_4 = \varepsilon_4 \operatorname{sgn}(x_2 - \hat{x}_2) \end{cases}. \tag{4}$$

Where, $\alpha_1 = \frac{R}{L-M}$, $\alpha_2 = \frac{1}{L-M}$, $x_1 = I_a - I_b$, $x_2 = I_b - I_c$, $x_3 = E_{ab}, x_4 = E_{bc}$, $\varepsilon_1, \varepsilon_2$ are the line current observer gain, $\varepsilon_3, \varepsilon_4$ are the back-EMF observer gain, symbol' $\wedge$ ' means estimated value of corresponding variables, 'sgn' represents the signum function.

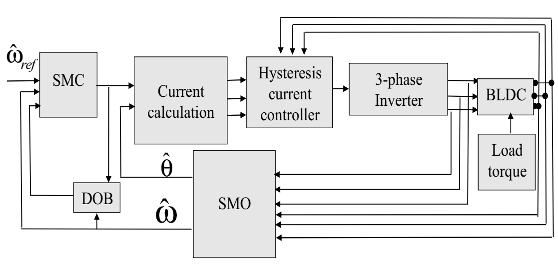


Figure 2. Proposed scheme

Comparing the equation (1) and equation (4), the error dynamics is given as:

$$\begin{cases} \dot{e}_1 = -\alpha_2 e_3 - \varepsilon_1 \operatorname{sgn}(e_1) \\ \dot{e}_2 = -\alpha_2 e_4 - \varepsilon_2 \operatorname{sgn}(e_2) \\ \dot{e}_3 = -\varepsilon_3 \operatorname{sgn}(e_1) \\ \dot{e}_4 = -\varepsilon_4 \operatorname{sgn}(e_2) \end{cases}. \tag{5}$$

Where $e = x - \hat{x}$.

C. High-speed Sliding mode observer

1) The traditional SMO using the signum function suffers from chattering and needs to be passed through the LPF before the back-EMF is estimated. It causes a time delay and requires extra compensation. To eliminate the undesirable chattering, a sigmoid function (6) is adopted in this research as the switching function. The sigmoid function is defined as follows.

$$sigmoid(s) = \frac{2}{1+\exp(-\alpha s)} - 1. \tag{6}$$

2) It is necessary to adjust the observer gain according to the reference rotational velocity, which affects the switching delay and observation speed. Therefore, the observer gain ε' is adjusted according to the rotational velocity as

$$\varepsilon' = \frac{\omega_{ref}}{\omega_{\max}} \varepsilon. \tag{7}$$

Where ω_{ref} is the reference velocity, $\omega_{\max}$ is the maximum speed, ε is the observer gain at maximum speed input.

3) The normal speed reaching is slower than that by exponential reaching law (8). Exponential reaching law can increase the dynamic quality, decrease the approaching time and make the velocity really small when the moving point reaches the switching surface to ensure that the moving point reaches the switching surface at any point in the state space for a limited time.

$$\dot{s}(t) = -\varepsilon' sig(s(t)) - ks(t) \quad \varepsilon > 0, k > 0. \tag{8}$$

Where k is exponential observer gain. Fig. 1 shows the structure of the proposed high-speed SMO.

D. Rotor Position and Speed Estimation

Using the estimated three phase-to-phase back-EMF obtained by the improved sliding mode observer, the position and speed signals could be calculated easily. A method which based on $E_{\max(\text{phase to phase})}$ and rotor speed is used [6].

$$\omega_r = \frac{E_{\max(\text{phase to phase})}}{2K_{EMF}}. \quad (9)$$

where K_{EMF} is the constant of the back-EMF.

The six rotor positions of the motor could be easily determined form the relation of phase currents and phase-to-phase back-EMF.

E. Stability Analysis of the Sliding Mode Observer

In order to verify the stability of the aforementioned SMO [5], the Lyapunov function is selected as

$$V(e) = \frac{1}{2}(e_1^2 + e_2^2). \quad (10)$$

To make sure that $V(e)$ is a globally asymptotically stable, the observer gain value is chosen in such a way that $\varepsilon_1' > \alpha_2 |e_3|_{\max}, \varepsilon_2' > \alpha_2 |e_4|_{\max}$, therefore $\dot{V}(e) < 0$ for $e \neq 0$ and $\dot{V}(e) = 0$ for $e = 0$.

III. DESIGN OF SMC SPEED CONTROLLER

In the traditional BLDC motor control system, PI controller has been widely used for its simplicity and practicality. However, it is not always applied for sensorless control when the feedback signals are estimated rather than measured.

In this proposed control scheme, SMC is robust to internal parameter variations and disturbance once system trajectory reaches and stays on the sliding surface. In addition, DOB is used, and the estimated system disturbance is considered as the feedforward compensation to compensate the controller.

A. SMC Controller

Use the state variables as follows.

$$\begin{cases} X_1 = \omega_{ref} - \omega \\ X_2 = \dot{X}_1 = -\dot{\omega} \end{cases}. \quad (11)$$

Where ω_{ref} is the given speed; ω is the actual rotary speed.

According to the (2), (3) and (11), the following second-order nonlinear model is used to describe the SMC system based on brushless DC motors.

$$\begin{cases} \dot{X}_1 = -\dot{\omega} = -\frac{k_t I}{J} + \frac{T_L}{J} \\ \dot{X}_2 = -\ddot{\omega} = -\frac{k_t \dot{I}}{J} \end{cases}. \quad (12)$$

If $u = \dot{I}$, then the state equation could be described as

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{k_t}{J} \end{bmatrix} u. \quad (13)$$

Then sliding-mode surface is chosen as follows:

$$s_1 = cX_1 + X_2. \quad (14)$$

Where $c > 0$, which could guarantee the asymptotic stability of the sliding mode. Take its partial respect, the following equation is given as follows.

$$\dot{s}_1 = c\dot{X}_1 + \dot{X}_2 = cX_2 - \frac{k_t}{J}\dot{I}. \quad (15)$$

In order to improve the dynamic quality, exponential reaching law is typically chosen. So combing it with equation (15), the control input I is designed as follows:

$$I = \frac{J}{k_t}\int (cX_2 + \varepsilon_5 \operatorname{sgn}(s_1) + k_3 s_1)\, dt, \varepsilon_5 > 0, k_3 > 0 \quad (16)$$

B. Disturbance Compensation

Disturbance Observer (DOB) for load torque has been adopted as a useful tool for disturbance rejection [10]. For this structure, we have

$$y = \frac{G \cdot G_n}{G_n + (G - G_n)Q} u_r + \frac{G \cdot G_n(1-Q)}{G_n + (G - G_n)Q} d. \quad (17)$$

Where u_r, d ,and y are the current reference input, load torque disturbance and speed output, respectively. $G(s)$ and $G_n(s)$ represent plant and nominal model of plant. $Q(s)$ is the transfer function for a low pass filter.

Transfer functions for the nominal plant and low pass filter are given by

$$G_n(s) = \frac{K_t}{Js + B}, Q(s) = \frac{1}{\tau_D + 1}$$

Where τ_D is the time constant related to the bandwidth which is chosen according to the bandwidth of load torque and the sampling period.

IV. MAIN RESULTS

A. Proposed Scheme

Fig.2 shows the proposed sensorless scheme combing SMC with two observers, SMO and DOB. In this scheme, the SMO estimates the back-EMF (E_{ab}, E_{bc}) and provides the estimate position $\hat{\theta}$ and speed $\hat{\omega}$ .Essentially, the estimated load torque is considered as the feedforward part to compensate disturbances of aforementioned SMC method stated in (17).

B. Simulation Results of Estimation

In order to demonstrate the effectiveness of the proposed approach c in BLDC motor sensorless system, a simulation using MATLAB/Simulink environment is presented.

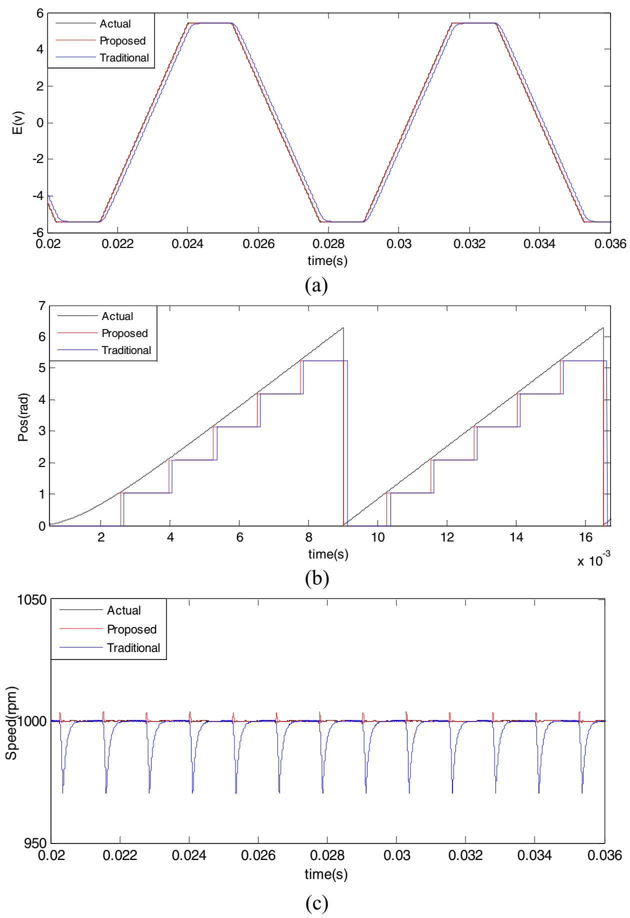


Figure. 3 Comparisons of results derived from the proposed and traditional observer at a speed of 1000 rpm:(a) actual and estimated back-EMF.(b) actual and estimated position.(c) actual and estimated speed

The estimated results of traditional SMO and the proposed SMO at a speed of 1000 rpm and 2500 rpm are shown in Figs.3 and 4. The comparison of actual and estimated back-EMF, position and speed derived from proposed and traditional method are shown in detail.

As shown in Fig. 3 (a) and Fig. 4 (a), apparently, the phase delay exists in traditional method and becomes greater at a speed of 2500 rpm. However, the estimated back-EMF derived from proposed method has nearly no apparent phase delay in both case. The estimated position form the proposed method is more accurate without the apparent phase delay too. The speed is calculated by the back-EMF directly, so the estimated speed using proposed way has less error. From Fig.3 (c) and 4 (c), the maximum speed error from traditional observer is about 29.6 rpm, whereas the maximum error from the proposed observer is approximately only 12.3% (3.65 rpm) of it. At a high reference speed, the maximum speed error from traditional observer is 185 rpm, whereas the maximum error from the proposed observer is approximately 9.5% (17.6 rpm) of it. As a result, the high-speed SMO is more accurate and effective in the estimation of speed and position for sensorless control.

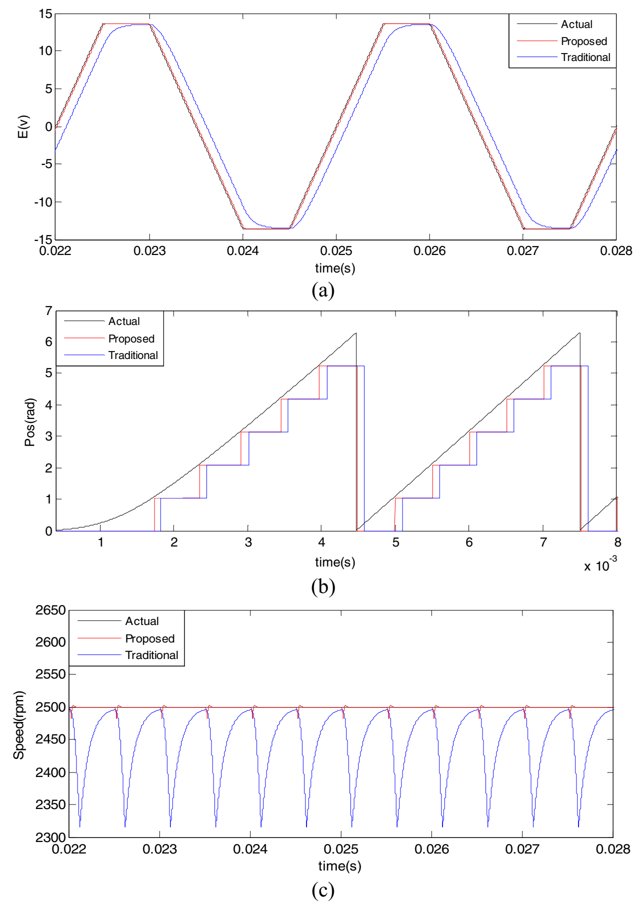
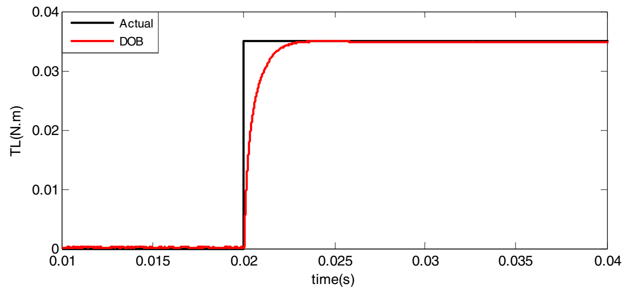


Figure. 4 Comparisons of results derived from the proposed and traditional observer at a speed of 2500 rpm:(a) actual and estimated back-EMF.(b) actual and estimated position.(c) actual and estimated speed.

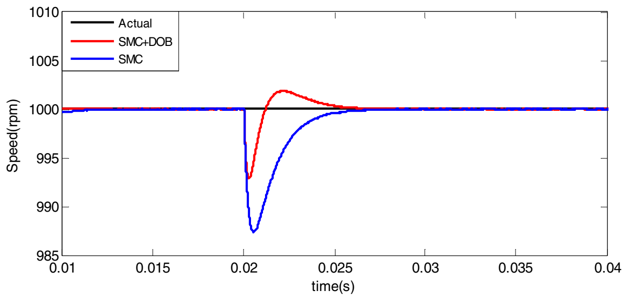
C. Simulation Results of Sensorless Control

The brushless DC motors runs without load at the beginning, and the load torque is added at $t = 0.2s$ .The simulation result at a speed of 2000 rpm with and without disturbance observer are shown in Figs. 5. Fig. 6 shows the speed responses using the proposed sensorless scheme combining SMC with DOB and the traditional scheme using PI (proportional-integral) controller. Fig.7 shows the speed responses at the speed of 1000 and 2500 rpm using the traditional observers and proposed observer based on the sensorless control scheme. The estimated speed and position signals are used for the speed loop control and the DOB generates a compensation signal for SMC.

It is obvious that the disturbance observer estimates the load torque exactly and quickly as shown in Fig .5 (a). When it is considered as the feedforward part to compensate disturbances, the speed fluctuation is smaller and the setting time is shorter as shown in Fig. 5 (b). Fig.6 indicates the speed response of SMC has no overshoot and better dynamic performance, so the SMC is more applicable to the sensorless speed control of BLDC system when compared to PI controller. From Fig.7, we know that



(a)



(b)

Figure. 5 Comparison results with and without disturbance observer in case of sudden load increase at 0.2s: (a) load torque command and estimated torque disturbance. (b) speed command and dynamic speed

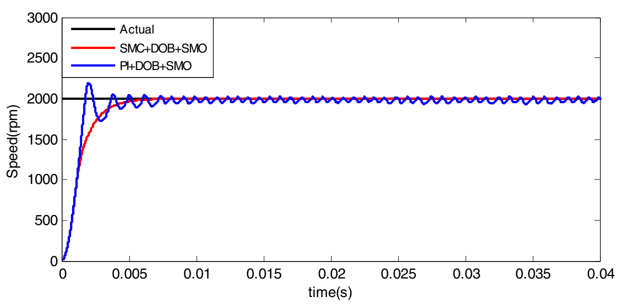
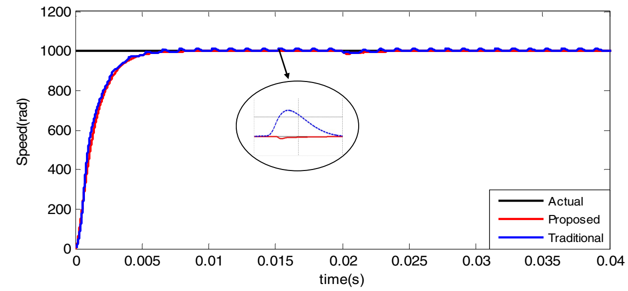


Figure. 6 Comparison results of speed responses with SMC and PI controller

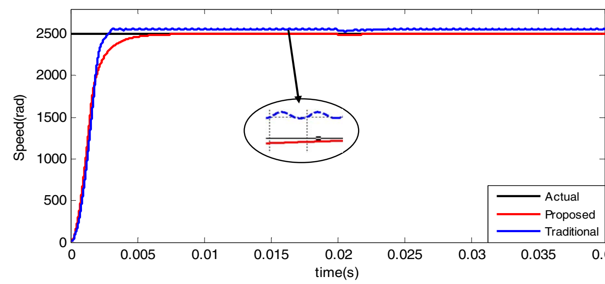
the speed response of proposed scheme has better performance and smaller steady error, especially at a high speed. In conclusion, the sensorlesss control scheme has satisfying disturbance suppression ability when the load is added suddenly.

V. CONCLUSION

This paper is focused on the problems existing in the back-EMF estimation of traditional SMO and the speed fluctuation caused by load torque. A sigmoid function with a flexible switching gain replaces the signum function, which improves the estimated accuracy. One SMC algorithm combined with the disturbances observer as a compensation part is proposed to suppress disturbances. The proposed composite control method that the combines adaptive SMO and the SMC with a disturbances observer is developed to further improve the performance of speed control and the load disturbance rejection ability. The simulation results have validated the proposed scheme.



(a)



(b)

Figure. 7 Comparison results using proposed and traditional SMO based on sensoreless control scheme: (a) speed responses at a speed of 1000 rpm. (b) speed responses at a speed of 2500 rpm.

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