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# Sensorless Control of PMSM Using a New Adaptive Sliding Mode Observer

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## Abstract

This paper proposes an adaptable sliding mode observer (SMO) which adds an estimation function of the stator resistance to the traditional sliding mode observer for the robust sensorless control of permanent magnet synchronous motor (PMSM) with variable parameters. Also a low-pass filter and additional position compensation of the rotor are used to reduce the chattering problem common in the conventional sliding mode observer. In this proposed observer, the chattering problem is eliminated by adopting a sigmoid function under the control of a switching function. By adding the estimation function of the stator resistance, the proposed observer can improve the estimation performance of the motor speed. It reduces the estimation error in the fast adjustment even in the situation that the stator resistance is varied in the sensorless operation environment. This control system has better efficiency than the traditional sliding mode observer as it reduces the number of integrators. The stability of proposed observer is verified by the Lyapunov method for the given observer gains, and the validity of the observer is demonstrated by simulations and experiments.

***Keywords :*** PMSM, Sensorless Control, Sliding Mode Control, Adaptive Sliding Mode Observer

## I. Introduction

Recently for the industrial machines, robots, and automobile, the usage of AC(Alternating Current) motors instead of DC(Direct Current) motors has been increased rapidly. The AC motor has more complex control system than the DC motor. However since there is no brush in the AC motor, the size of the AC motor can be smaller with the same power and the lifetime is much longer the DC motor. There are two types of AC motors: IM (Induction Motor) and PMSM (Permanent Magnet Synchronous Motor). The PMSM is very popular in AC motor applications since it is useful for the various speed control. The IM has simple structure and easy to build. However it is not so efficient as PMSM in terms of dynamic performance and power density[1]. Since PMSM receives the magnetic flux from the permanent magnet of the rotor, the precise position data are necessary for the efficient vector control. Generally, the rotor position can be detected by a resolver or by an absolute encoder. However the sensors are expensive and very sensitive to the environmental constraints such as vibration and temperature[2]. To overcome these problems, in stead of using the position sensors, the sensorless control methos has been developed to control the motor suing the estimated values of the position and velocity of the rotor[3-6].

This paper proposes a new sensorless control algorithm of PMSM. The proposed observer is easy to design and has robustness against design parameters. To guarantee the stability, a Lyapunov function is defined and is utilized in designing the observer. A stator resistance is estimated by the intermediate equations of Lypunov functions to derive stable system, while in the conventional sliding mode observer, the position and velocity of the rotor and the resistance of stator have been observed in integral forms all together. The stator resistance can be changed while it is running, which deteriorate the control performance unless it is compensated in real time.

## II. PMSM Model

In the case of sensorless control of the PMSM, the fixed frame model of stator needs to be developed regardless of the rotor position since the rotor position is estimated from the current values.

The state equations where the stator current is a state variable in voltage equation in the fixed frame can be represented as

$$\begin{aligned} \frac{d}{dt}i_\alpha &= -\frac{R_s}{L_s}i_\alpha - \frac{1}{L_s}e_\alpha + \frac{1}{L_s}v_\alpha \\ \frac{d}{dt}i_\beta &= -\frac{R_s}{L_s}i_\beta - \frac{1}{L_s}e_\beta + \frac{1}{L_s}v_\beta \end{aligned} \tag{1}$$

where, $i$, $e$, and $v$ represent current, counter electro-motive force, and voltage, respectively, in the fixed frame. $R_s$ and $L_s$ represent stator resistance and inductance, respectively.

Suppose that the speed of rotor changes slowly(), $(\dot{\omega} \approx 0)$ counter electro-motive force is represented as

$$\begin{aligned} \dot{e}_\alpha &= -\omega_r e_\beta \\ \dot{e}_\beta &= -\omega_r e_\alpha \end{aligned} \tag{2}$$

### 1. Sliding Mode Observer

There are shortcomings of chattering and time delay for the compensation of rotor position in the conventional sliding mode observer[7,8].
However, a new sliding mode observer resolves the problems of conventional sliding mode observer using a sigmoid function as switching function. The sigmoid function is represented as.

$$\begin{bmatrix} H(\bar{i}_\alpha) \\ H(\bar{i}_\beta) \end{bmatrix} = \begin{bmatrix} \left(\dfrac{2}{1+\exp(-a\bar{i}_\alpha)}\right) - 1 \\ \left(\dfrac{2}{1+\exp(-a\bar{i}_\beta)}\right) - 1 \end{bmatrix} \tag{3}$$

where, $\alpha$ is a positive constant to regulate the slope of sigmoid function and estimation errors of stator current are defined as $\bar{i}_\alpha = \hat{i}_\alpha - i_\alpha$, $\bar{i}_\beta = \hat{i}_\beta - i_\beta$.

Lyapunov function for existence condition of sliding mode is defined as

$$V = \frac{1}{2}s^T s = \frac{1}{2}(s_\alpha^2 + s_\beta^2) \tag{4}$$

where, sliding surface are $s_\alpha = \bar{i}_\alpha$, $s_\beta = \bar{i}_\beta$.

If $\dot{V} = s^T \dot{s} < 0,$ , the sliding mode exists, and the sliding surface is represented as

$$\begin{bmatrix} \dot{s}_\alpha & \dot{s}_\beta \end{bmatrix}^T = \begin{bmatrix} s_\alpha & s_\beta \end{bmatrix}^T = \begin{bmatrix} 0 & 0 \end{bmatrix}^T \tag{5}$$

From Eq. (5), the new terms are derived as

$$\begin{aligned} (kH(\bar{i}_\alpha))_{eq} &= \hat{e}_\alpha \\ (kH(\bar{i}_\beta))_{eq} &= \hat{e}_\beta \end{aligned} \tag{6}$$

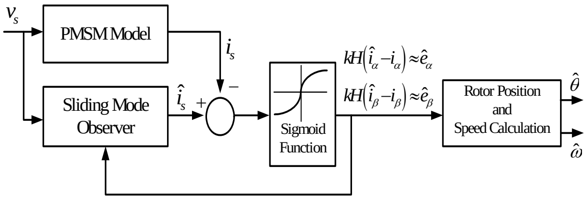


Fig. 1 Improved sliding mode observer

Figure 1 represents the block diagram of improved sliding mode observer. To resolve the chattering problems, the sigmoid function is serially connected to the sliding mode control. The speed and position of the rotor have been calculated by Eq. (6).

## Ⅲ. Proposed Sliding Mode Observer

Chattering problem in sliding mode control is solved applying proposed observer that used switching function by sigmoid function and estimated the stator resistance.

### 1. Adaptive Sliding Mode Observer

Sliding mode observer is composed by PMSM current equation in rest frame of (1) as following.

$$\begin{aligned} \frac{d}{dt}\hat{i}_\alpha &= -\frac{\hat{R}_s}{L_s}\hat{i}_\alpha + \frac{1}{L_s}v_\alpha - \frac{1}{L_s}kH(\hat{i}_\alpha - i_\alpha) \\ \frac{d}{dt}\hat{i}_\beta &= -\frac{\hat{R}_s}{L_s}\hat{i}_\beta + \frac{1}{L_s}v_\beta - \frac{1}{L_s}kH(\hat{i}_\beta - i_\beta) \end{aligned} \tag{7}$$

### 2. Estimation of Stator Resistance and the Observer Gain $k$

For the PMSM sensorless control, the estimation of the stator resistance that is robust the change of parameter set the Lyapunov function as follows.

$$V = \frac{1}{2}s^T s + \frac{1}{2}(\hat{R}_s + R_s)^2 \tag{8}$$

It is supposed that the rotor speed is constant during the one period and then the differential equation of (8) and the sliding surface( $s$ ) are expressed the differential equation of the Lyapunov function as (9).

$$\dot{V} = s^T\left[(\hat{A}-A)\hat{i}_s + A(\hat{i}_s - i_s) + B(e_s - kH(\bar{i}_s))\right] + \bar{R}_s\dot{\hat{R}}_s \quad (9)$$

where, $\hat{A} = -\frac{\hat{R}_s}{L_s}I,\ A = -\frac{R_s}{L_s}I,\ B = \frac{1}{L_s}I,\ \bar{R}_s = \hat{R}_s - R_s$

System of observer is stable from Lyapunov stability theory, must satisfy $V > 0$ and $\dot{V} < 0$. Therefore, (9) is expressed as (10) and (11)

$$s^T\left[(\hat{A}-A)\hat{i}_s\right] + \bar{R}_s\dot{\hat{R}}_s = 0 \quad (10)$$

$$s^T\left[A(\hat{i}_s - i_s) + B(e_s - kH(\bar{i}_s))\right] < 0 \quad (11)$$

From Eq. (10), the estimation of the stator resistance can be done as follows:

$$\dot{\hat{R}}_s = \frac{1}{L_s}(\bar{i}_\alpha\hat{i}_\alpha + \bar{i}_\beta\hat{i}_\beta) \quad (12)$$

To keep the sliding mode observer proposed in this paper stable, the observer gains should satisfy the inequality condition (11). The condition (11) is described in more detain as follows:

$$\begin{aligned}&-\frac{R_s}{L_s}((\bar{i}_\alpha)^2 - (\bar{i}_\beta)^2) + \frac{1}{L_s}(e_\alpha\bar{i}_\alpha - \bar{i}_\alpha kH(\bar{i}_\alpha))\\ &\qquad + \frac{1}{L_s}(e_\beta\bar{i}_\beta - \bar{i}_\beta kH(\bar{i}_\beta)) < 0\end{aligned} \quad (13)$$

where the observer gain can be derived as

$$k \geq \max\left(|e_\alpha|, |e_\beta|\right) \quad (14)$$

### 3. Improved Adaptive Sliding Mode Observer

The conventional adaptive sliding mode observer uses Lyapunov function, and it is s method to estimate position and speed of rotor and stator resistance at the same time. To estimate the position and speed of rotor, the integral operations are performed as follows[9].

$$\begin{aligned}\hat{\omega}_r &= \int\dot{\hat{\omega}}_r\\ \hat{\theta} &= \int\hat{\omega}_r\end{aligned} \quad (15)$$

Digital low-pass filters are mainly used to do integral operations in an actual system. Notice that since the digital low-pass filter causes time-delay, the performance of system goes down.

The proposed observer(16) in this paper, reduces the influence of estimation error caused by the parameter changes in the conventional adaptive control and calculates position and speed of rotor using the a new sliding mode observer. As the result, it improves the system performance.

$$\hat{\theta} = -\tan^{-1}\left(\frac{\hat{e}_\alpha}{\hat{e}_\beta}\right),\ \hat{\omega}_{\mathrm{r}} = \frac{d}{dt}\hat{\theta} \quad (16)$$

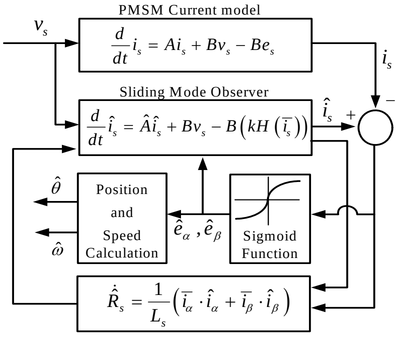


Fig. 2 Proposed sliding mode observer

## Ⅳ. Experimental Results

**F**igure 3 compares the results of velocity responses against a step input of 3000 rpm for conventional adaptive slide mode and for the proposed sliding mode observer.

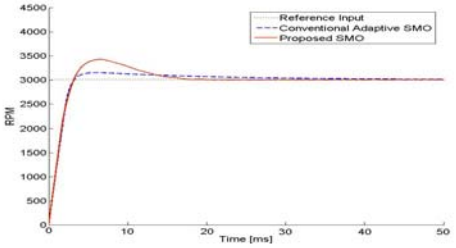
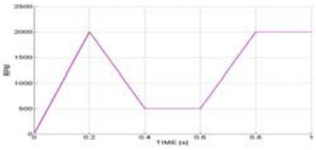


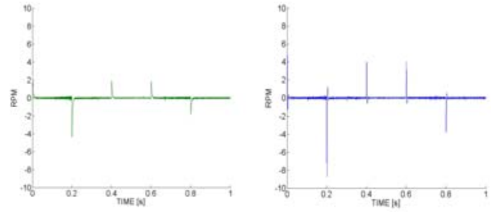
Fig. 3 Response property about step input

The conventional method represents settling time of 40 ms and overshoot of about 6.7%. The proposed method represents settling time of 18 ms and overshoot of about 15%. The proposed method is faster response than the conventional method.

Figure 4 shows the estimated speed error against the reference speed when it is changed along the time.



(a) RPM Change



(b) conventional observer (c) proposed observer

Fig. 4 Comparison the estimated speed error about speed change

Figure 4(a) shows the reference rpm change for 1 second. Figure 4(b) shows that the conventional method has the maximum speed error about 4 rpm and estimated speed of 12 ms. However the proposed method in Figure 4(c) has the maximum speed error of about 8 rpm and estimated speed of 6 ms. The proposed method is twice as fast as convention method in the estimated speed. However the proposed method has larger estimation error than the conventional method.

Figure 5 shows response property when initial stator resistance value is changed from 0.013 ohms to 0.13 ohms

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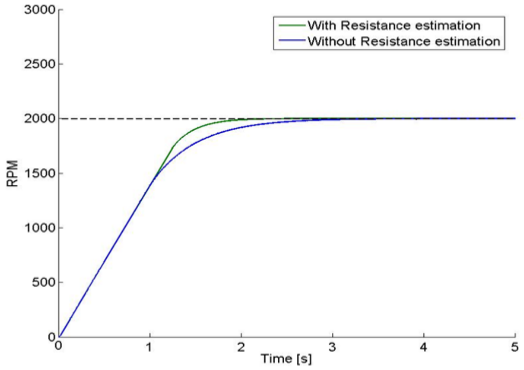

Fig. 5 Comparison of response property by initial resistance value change

It shows that response with the stator resistance estimation is faster than without the stator resistance estimation about 1 second.

## Ⅴ. Conclusions

This paper proposed a new sliding mode control for robust sensorless system of PMSM. Chattering problem in sliding mode control was resolved using a sigmoid function as the switching function. The stator resistance estimator was employed to reduce the estimated error with parameter changes. Proposed control system has fast response by reducing integral operations of conventional adaptive sliding mode observer. The superiority of the algorithm has been confirmed through simulations and experiments. As a future research, it is necessary to reduce both overshoot and speed error by adjusting gains based on heuristic method.

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