The Position and Speed Estimation of Switched Reluctance Motor using Sliding Mode Observer

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Abstract

For the speed control of motors, the position or speed sensors are necessary to obtain the position information of the rotor. Specially, SRM(Switched Reluctance Motor) needs an accurate rotor position data because both the rotor and the stator have a salient pole structure.

High functional sensors like resolver or encoder are expensive and have complex connecting lines to the controller so the pure signals are apt to be mixed with noises.

In the sight of SRM drives, the high temperature, heavy dust, and the EMI surroundings reduce the reliability of speed and position sensors. Therefore, the speed and position sensorless control algorithms using observer have been accepted widely.

In this paper An adaptive sliding observer is described to control the SRM without speed or position sensors. The adaptive sliding observer is set on the basis of variable structure control theory. The sliding surface is constructed by current error terms and this surface guarantees the errors converge to 'zero'. The stability of observer is affirmed by Lyapunov stability analysis and popov's hyper stability theory.

1. Introduction

Energy saving and precision problems are issued in the areas of motor control. So the companies and individuals demand the high efficient and high power factor motor. In this sight, the widely used BLDC(Brushless DC)Motor is better than Induction motor at the points of efficiency and size. But the permanent magnet increase the price and the space for rotor and stator.

SRM has been attracted due to the absence of magnets, rotor conductors, and brushes. And SRM has a higher system efficiency in a wide speed range than induction motor.

But the SRM needs the sensors to gain the rotor position as encoders, resolver, and Hall effect sensors. So, additive expense problem has been occurred. Moreover, the usage of these sensors decreases the reliability of system in the EMI environments. Therefore, speed or position control without sensors has been studied widely[1][2][3][4]. In the sensorless area, the speed and position estimation methods are researched by hardware methods and software methods using high functional microprocessor. But these methods have many difficulties to get the speed information in wide speed range because the parameters of motor vary terribly by currents, fluxes and back-EMF, etc. So the good performance of the speed estimation is not appeared.

SRM is an inherent nonlinear system, and the proposed adaptive sliding observer is robust for the parameter variation and the disturbance. We used the PWM current control with the angle control for the rapid speed response. Experimental results verifies the estimation performance of this observer.

2. The Structure of SRM

Fig1. shows the typical structure of 8/6 SRM. The shape of rotor and stator is the salient poles, and motor ratings are showed by Table 1. Nonlinear inductance profile is required to be linearlized for application to observer and system stability.

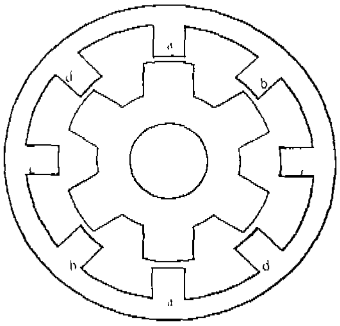


Fig1. SRM structure

Table 1. Motor Ratings

Phases stator/rotor poles	8/6
Stator pole-arc	22.8[Deg]
Rotor pole-arc	24.6[Deg]
Phase resistance	1.6
Rated Torque	0.8[Nm]
Rated Speed	4000[rpm]
Dc-link Voltage	200[V]

Fig2. shows a real inductance profile versus position per phase. Since a flux of the phase is saturated by the phase currents, the inductance profile has a non-linearity. Also, Fig2 shows that the non-linearity of the inductance profile increases by increasing the phase currents. Therefore, the linear inductance profile as Fig3 is used in this paper because the phase currents in the experimental condition are 3A.

The maximum value of a phase inductance is 62[mH], and the minimum value is 10[mH].

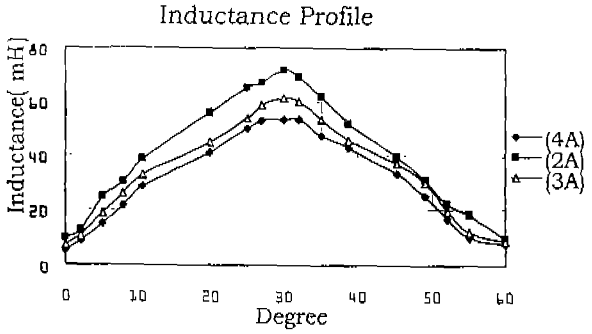


Fig2. Real Inductance Profile

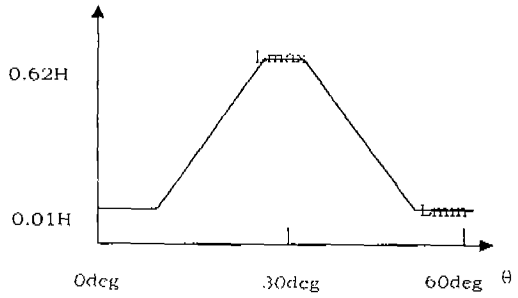


Fig3. Ideal Inductance Profile versus position

3. The Speed Control of SRM.

3.1 States equation Modelling

The voltage and torque equation of SRM's are shown as below.

$$\begin{aligned} V &= Ri + \frac{d\lambda(\theta,i)}{dt} \\ &= Ri + L(\theta,i)\frac{di}{dt} + \frac{dL(\theta,i)}{d\theta}\omega i \qquad (1) \\ T(\theta,i) &= J\frac{d\omega}{dt} + B\omega + T_l \\ &= \frac{1}{2} i^2 \frac{dL(\theta,i)}{d\theta} \end{aligned}$$

By using (1), the curent and speed equation are acquired as (2)

$$\begin{aligned} \frac{d}{dt} i &= \frac{-R}{L} i - \frac{dL}{Ld\theta}\omega i + \frac{V}{J} \\ \frac{d}{dt}\omega &= -\frac{B}{J}\omega + \frac{T-T_L}{J} \\ &= \frac{1}{2J} i^2 \frac{dL}{d\theta} - \frac{T_L}{J} - \frac{B}{J}\omega \qquad (2) \end{aligned}$$

where,

$i = [\, i_a \, i_b \, i_c \, i_d \,]^T$

$L = [\, L \;\; L_b \, L_c \, L_d]^T$

3.2 Current and Angle Control

PWM rule having the hysterisis band is applied to control the phase current of SRM.

In this PWM control, the upper and lower limits are defined by $i_{ref} \pm \frac{\Delta i}{2}$ where i_{ref} = reference current and Δ= hysterisis band as showed in Fig4.

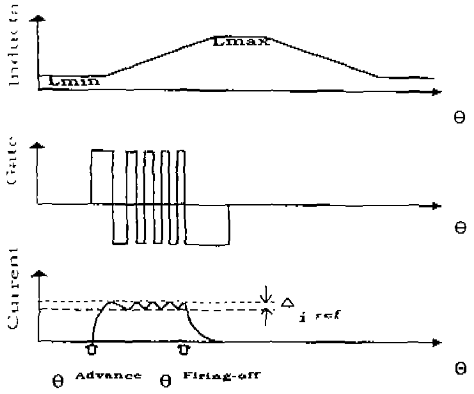


Fig4. Angle and PWM Current Control

Since the motor phases have considerable inductance and as the speed increases, the back-EMF influences on the distortion of current waveform.

The effect of back EMF increases the time required for the current to rise to the commanded level.

To prevent this problem, the current of each phase should be switched on earlier so that the current may be at commanded level before the rising slope of the inductance is reached. Therefore, θ_{adv} and θ_{fir} in Fig4. must be determined utilizing the speed.

4. Adaptve Sliding Observer

In the nonlinear system, the parameter identification is difficult so, the adaptive sliding mode observer theory is suitable to the nonlinear SRM system, because the sliding observer theory has an endurance against the parameter variation and disturbance. For applying this theory to the SRM, we should assume several things that for one sample cycle the parameter variation terms could be neglected and this sliding observer approximates the inductance profile linearly. The proposed observer designed as follow.

$$\begin{aligned} \frac{d}{dt} i_e &= \frac{-R}{L_e} i_e - \frac{dL_e}{L_e d\theta_e}\omega_e i_e \\ &\quad + \frac{V}{L_e} + K_s(i - i_e) \qquad (3) \end{aligned}$$

where,

$i_e = [\, i_{ae} \, i_{be} \, i_{ce} \, i_{de} \,]^T$

$L_e = [\, L_{ae} \, L_{be} \, L_{ce} \, L_{de}]^T$

$$where,\ K_s = K_{sa} + K_{sb}$$

$$K_{sa} = K_{s1}\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}$$

$$K_{sb} = K_{s2}\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}\begin{bmatrix}sgn(i_{ae})\\sgn(i_{be})\\sgn(i_{ce})\\sgn(i_d)\end{bmatrix}$$

The sliding hyper surface is defined as stimation error terms in (4) and the yapunov functon is (5)

$$s = i - i_e - K_e\, sgn(i) \tag{4}$$

where, K_e: *Current feedback gain*

$$V = s^T s \tag{5}$$

For Lyapunov stability analysis Equation(5) ould be differentiated like (6).

$$\frac{dV}{dt} = 2s\frac{d}{dt}s < 0 \tag{6}$$

$$\frac{dV}{dt} = 2s[As - \triangle A\, i_e - \triangle Bv - K_s s]$$

where,

$$A = [-\frac{R}{L} - \frac{\omega}{L}\frac{dL}{d\theta}]I\ , \quad \triangle A = A - A_e$$

$$A_e = [-\frac{R}{L_e} - \frac{\omega_e}{L_e}\frac{dL_e}{d\theta_e}]I\ , \quad \triangle B = L_d - L_{de}$$

I = Identity Matrix

If the parameter perturbation terms is eglected in the (6). $\triangle A$ and $\triangle B$ is zero'. and become (7).

$$\frac{dV}{dt} = 2s[A\,s - K_s s] \tag{7}$$

Then the K_s should satisfy following conditions for stability.

$$K_{s1} > K_{s2} > A \tag{8}$$

If the current errors are converged to 'zero' by (8). then the speed estimation equation is as (9)

$$\begin{aligned}\frac{dV}{dt} &= 2\,s[-\triangle A\, i_e - K_{sb}s]\\ &= \frac{1}{L_e}\frac{dL_e}{d\theta_e}(\omega_e - \omega)i_e K_e sgn(i)\\ &\quad - K_{sb}(i - i_e)sgn(i)\end{aligned} \tag{9}$$

If the (9) is 'zero', then satisfy the equation (6) and the speed estimation error could be extracted like equation (10)

$$\triangle\omega = K_{sb}(i - i_e)L_e\frac{d\theta_e}{dL_e}\frac{1}{i_e} \tag{10}$$

The speed estimation error is proportional to the current error and gain K_{sb}. Therefore, the speed estimation equation could be written as (11).

$$\begin{aligned}\omega_e &= K_P(i - i_e)sgn(i_e)\\ &\quad + K_I\int(i - i_e)sgn(i_e)\,dt\end{aligned} \tag{11}$$

On the basis of the (11) the observer's efficient estimation capability could be acquired.

5. Experimental Results

The total block diagram is showed in Fig 5.

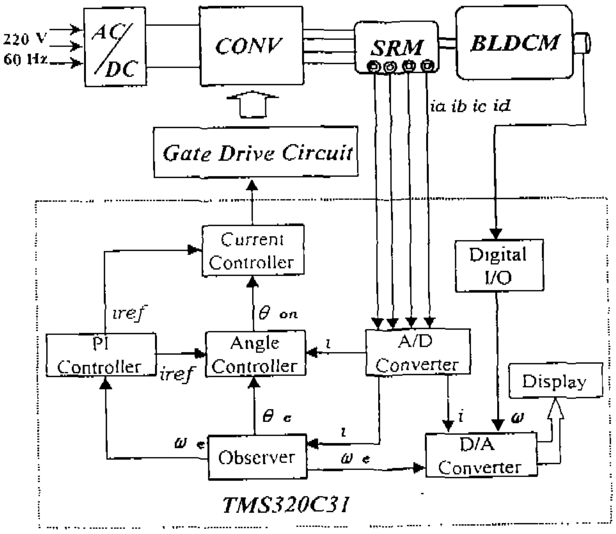


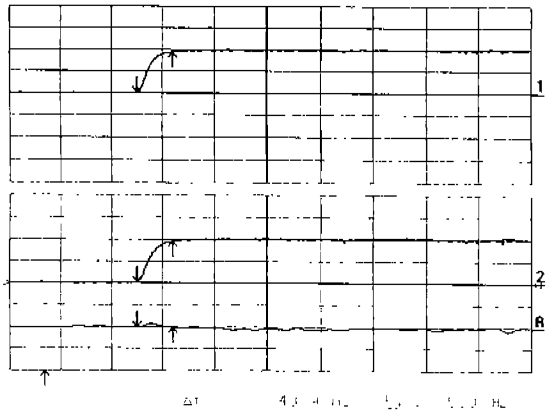
Fig5. Adaptive Sliding System

The main controller which is on the basis of DSP(Digital Signal Processor-TMS320C31) is a part making a current estimation, speed identification and position estimation, PI control, the calculation of advance and firing-off angles. BLDC motor is used for the load and the rating is shown in Table 1.

Table 2. Load Rating Data (BLDCM)

Stall Torque	3.8N.m	Rated Current	18A
Damping Coefficient	0.003	Inertia	0.18
Brake Maximum Torque	3.2N.m	Inertia Moment	0.064

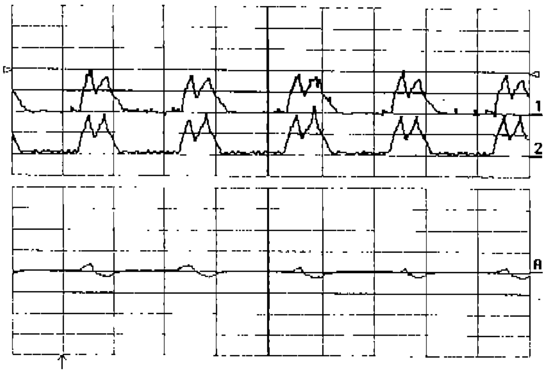
The experiment results are performed in 0.4 N · m loads. Fig 6 shows the real speed(Ch1), estimated speed(Ch2) and their error(ChA). It ascertains the speed estimation performance with fast response for the reference. The time of response for the reference is nearly 0.35sec. The estimated speed tracks the real speed stably in spite of the applied loads and parameter variations.



Ch1 500rpm div Ch2 500rpm div ChA 250rpm div 0.5sec div

Fig6. Experimental results of Speed

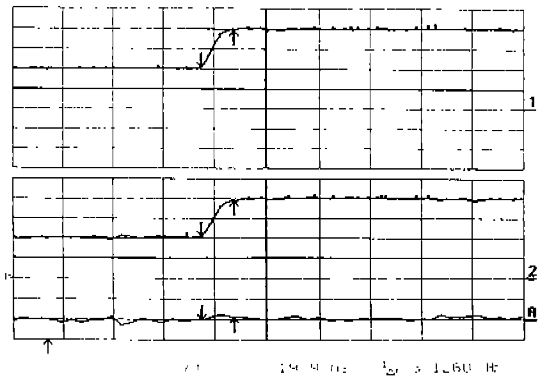
Fig7 presents the real current(Ch1), estimated current(Ch2) and the error(ChA). From these results, the current is estimated stably with a little error.



Ch1 2[A]/div Ch2 2[A] div ChA 2[A]/div 2[ms]/div

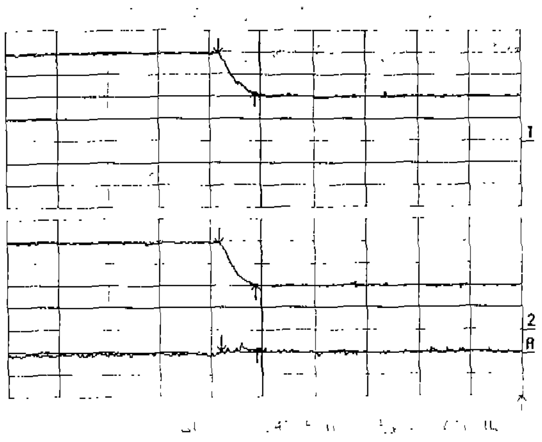
Fig7. Experimental results of one phase current

In the case that the accelerating speed reference is commanded, the real speed(Ch1), estimated speed(Ch2), and their error(ChA) are shown in Fig 8. A little chattering is occurred in the speed response. But the estimation errors are converged to 'zero' as time goes on. When the decelerating speed reference is commanded, small transient errors on the changing point of speed are shown as Fig 8. In each cases this observer shows the stable speed estimation performance and rapid speed response without overshoot. But the chattering in the speed estimation is occured. That is the result of using the sliding hyper plane which operates as the discontinuous control input.



Ch1 500rpm/div Ch2 500rpm/div ChA 250rpm/div 0.5sec/div

Fig8. Speed in the acceleration command



Ch1 500rpm div Ch2 500rpm/div ChA· 250rpm div 0.5sec/div

Fig9. Speed in the deceleration command

6. Conclusion

In this paper the innovated sliding mode observer is proposed to estimate rotor speed and position of SRM without speed and position sensors . The experimental results verified the proposed the estimation abilities of observer. The estimated speed error converges to 'zero' as the estimation current errors does 'zero'. But the small chattering in the speed is occurred at high speed region because of discontinuous control input terms in observer. In a wide speed range, The adaptive sliding observer is robust against the parameter variation and load disturbance and has the good estimation performance.

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