The Control of Switched Reluctance Motor using MRAS without Speed and Position Sensor

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Abstract - The speed control of SRM(Switched Reluctance Motor) needs the accurate position and speed data of rotor. This information is generally provided by a shaft encoder or resolver. In some cases, the environment in which the motor operates may cause difficulties in maintaining the satisfactory position detection performance. Therefore, the elimination of the position and speed sensor has gained wide attention. In this paper, a new algorithm for estimation of rotor position and speed is described for the SRM drives. This method uses a nonlinear adaptive observer using the MRAS(Model Reference Adaptive System). The observer is proved by Lyapunov Stability Theory. This algorithm was implemented with a TMS320C31 DSP. Experiment results prove that the observer is able to estimate the speed and position with a little errors.

1. Introduction

In recent years, the SRM(switched reluctance motor has received considerable attention for the variable speed drive application. Its simple construction due to the absence of magnets, rotor conductors, and brushes, and high system efficiency over wide speed range make the SRM drive an interesting alternative to compete with permanent magnet brushless dc motor and induction motor drives. However, the need for the direct rotor position sensors to commutate the current from phase to phase synchronously according to the rotor position has excluded SRM from many cost sensitive applications.

Encoders, resolvers, or Hall sensors attached to the shaft have been normally used to supply the rotor position or speed, but the use of these sensors may lead to reliability problems in harsh environments, and may become an important part of the overall drive system cost. So many researchers have dealt with the problem of eliminating the position sensors by measuring terminal voltages and current. There are two principal methods in the area of indirect position sensing.

The first estimation method is the waveform detection method that determines the position of the rotor by using the inductance or mutual inductance effects. This method imposes limitations on the operating range of drives[4].

The second method is an observer application that reconstructs the state of the SRM drive system on the basis of known system inputs and system measurements. This method has a drawback that the performance of the observer may not be fast enough for transient operation because the linear observer theory neglects the non-linearity by means of very large rotor inertia.

In this paper, a new method for the speed and position sensorless control in SRM using MRAS is described. The proposed observer overcomes the non-linear problems by considering the perturbation terms. This method uses two models for the purpose of estimating the speed and position. The first model is the system of the SRM, and the second model is the system of observer. There are errors between two models due to the parameter uncertainties which mean perturbations of the speed and position, and these errors are appeared the differences between the real currents and the estimated currents. Because the estimation current errors include the variation of the speed and position, the speed and position of rotor can be observed from them.

This paper is constructed as follows. Section 2 shows the structure of SRM and inductance profile. The control method is described in Section 3, and the estimation method using MRAS is discussed in Section 4. Section 5 verifies the control scheme and estimation scheme by experiments.

2. The Structure of SRM

The structure of 8/6 SRM is shown in Fig1. The shape of the rotor and stator is salient type, and motor ratings are shown in Table1.

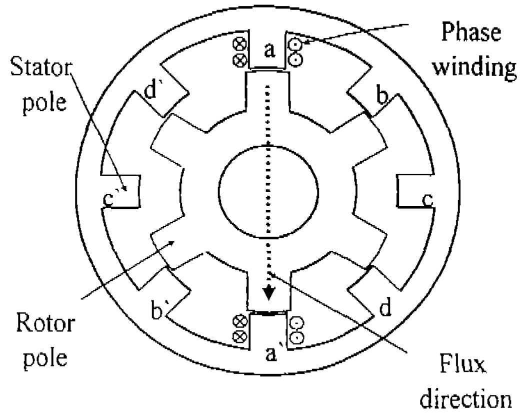


Fig1. The structure of 8/6 SRM

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[N.m]
Rated Speed	4000rpm
Dc-link Voltage	200V

Fig2. shows a real inductance profile versus position per phase. Since the flux of phases is saturated by the phase currents, the inductance profile shows non-linear properties.

Fig2. shows that the non-linear properties of the inductance profile are increased by raising the phase currents. Therefore, the linear inductance profile as shown in Fig3, is adopted in this paper because the phase currents in the experimental condition are nearly 3A levels.

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

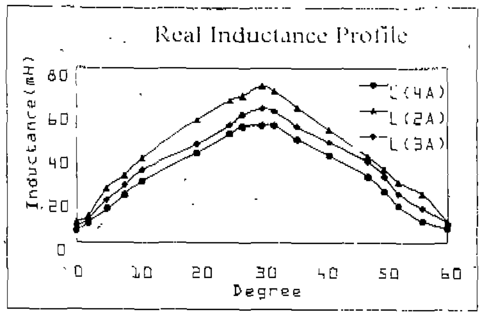


Fig2. Real Inductance Profile versus position.

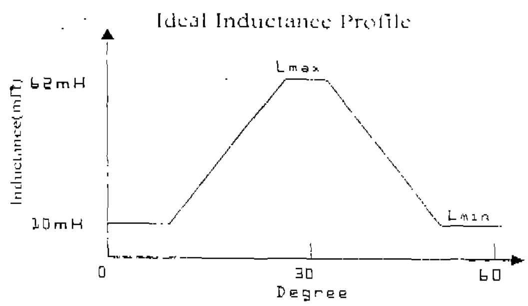


Fig3. Ideal Inductance Profile versus position

3. The Speed Control of SRM.

3.1 States Equation of SRM

The voltage and torque equations of SRM could be written as (2.1).

$$\begin{aligned} V &= Ri + \frac{d\lambda(\theta, i)}{dt} \\ &= Ri + L(\theta, i)\frac{di}{dt} + \frac{dL(\theta, i)}{d\theta}\omega i \qquad (2.1) \\ T(\theta, i) &= J\frac{d\omega}{dt} + B\omega + T_L \\ &= \frac{1}{2} i^2 \frac{dL(\theta, i)}{d\theta} \end{aligned}$$

By using (2.1). the curent and speed equation are acquired as(2.2).

$$\begin{aligned} \frac{d}{dt} i &= \frac{-R}{L} i - \frac{dL}{Ld\theta}\omega i + \frac{V}{J} \\ \frac{d}{dt}\omega &= -\frac{B}{J}\omega + \frac{T - T_L}{J} \qquad (2.2) \end{aligned}$$

where,

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

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

3.2 Control of Current and Angle

The current is controlled between two current levels equal to $i_{ref} \pm \triangle i/2$, where i_{ref}= reference current, and $\triangle$= hysteresis band. The real current is followed by the reference current as shown in Fig4.

A square current waveform at the conduction period of the phase is required to gain the constant torque. However, this is not practical since the motor phases have considerable inductance and it takes times for the current to rise and fall. Also, when the speed begins to increase, the back EMF value increases, and this increased value reduces the effective voltage applying to the phases.

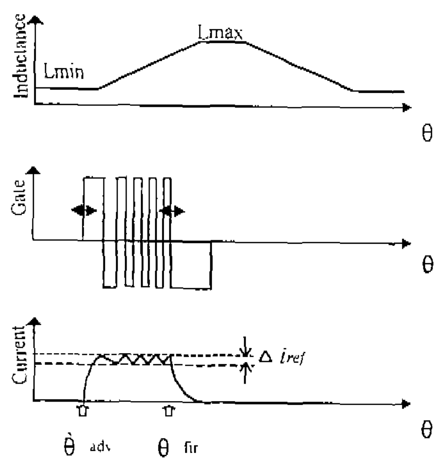


Fig4. Current and Angle Control

The effect of the 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 the commanded level before the rising slope of the inductance begins. Therefore, θ_{adv} and θ_{fir} in Fig4. must be determined by utilizing the speed.

The advance and firing-off angles for the range of speeds are calculated straightforward from the current state equation (2.2). The solution of current state equation is (2.3).

$$i(t) = \frac{V-V_e}{R} + (i_0 - \frac{V-V_e}{R})e^{\frac{-t}{\tau}}$$
$$\theta = \omega_m t \tag{2.3}$$

where,
θ = *advance or fall angle*
i_0 = *Initial current*

The rising time or falling time of the current is calculated by (2.3) and could acquire the advance or the firing-off angle.

4. Observer using MRAS

In general, the state observer is linear but SRM's equation is nonlinear. Therefore, the application of the general Observer theory needs several assumptions.

1)In one sampling time, speed and the phase inductance of the SRM are constant
2)Inductance/position of rotor ratio is constant.
3)If they are not constant, the subtraction values between real value and estimation value have the uncertain quantity. Therefore, the state observer considering the uncertain parameters must be designed

On the basis of these assumptions, the state observer could be designed as followings.

$$\frac{d}{dt} i_e = \frac{-R}{L_e} i_e - \frac{dL_e}{L_e d\theta_e} \omega_e i_e + \frac{V}{L_e} + K(i - i_e) \tag{2.4}$$

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

4.1 Gain K of Observer

The eigenvalues of equation (2.4) must be lied in the left-half surface in s-plane as to stability theory. So the condition of the gain K stabilizing the estimated phase current of the observer is (2.5).

$$K > \frac{R}{L_e} + \frac{dL_e}{L_e d\theta_e}\omega \tag{2.5}$$

4.2 Adaptation Law - Speed Identification

As to the Lyapunov stability theory, Lyapunov function is defined as below.

$$V = e^T e + f \geq 0 \tag{2.6}$$

where,
$e = i_e - i$
f = *weighting function*

The derivative of (2.6) can be written as (2.7) and must be less than zero.

$$\frac{dV}{dt} = (\frac{de}{dt})^T e + e^T \frac{de}{dt} + \frac{df}{dt} < 0 \tag{2.7}$$

Equation(2.7) can be rewritten as followings.

$$\frac{dV}{dt} = -2e\Delta A e^T + 2e(A-K)e^T + \frac{df}{dt} \tag{2.8}$$

where,
$A = (\frac{-R}{L} i - \frac{dL}{Ld\theta}\omega i)I$
$A_e = (\frac{-R}{L_e} i_e - \frac{dL_e}{L_e d\theta_e}\omega_e i_e)I$
$\Delta A = [A - A_e]$
I = Identity Matrix

If the function f is defined as (2.9), equation(2.6) is satisfied.

$$f = K_f \frac{(\omega_{el} - \omega)^2}{L_e} \frac{dL_e}{d\theta_e} \tag{2.9}$$

Also, defining the speed identification

equation as (2.10), manipulating (2.8)-(2.10), we can obtain (2.11)

$$\omega_e = K_P(e\, i_e) + K_I \int (e\, i_e)dt = \omega_{eP} + \omega_{eI} \quad (2.10)$$

$$\frac{dV}{dt} = 2K_I K_I \frac{1}{L_c}\frac{dL_c}{d\theta_c}[(\omega_c - \omega)e i_c - (K_P e i_c)e i_c] - 2e^T \triangle A i_c \quad (2.11)$$

If K_P is set as $1/K_I$, then the equation (2.11) is as (2.12)

$$\frac{dV}{dt} = -2K_P \frac{dL_c}{d\theta_c}\frac{1}{L_c}(e\, i_c)^2 \quad (2.12)$$

Equation (2.12) is negative if $K_p > 0$, $\frac{dL_c}{d\theta_c} > 0$. Therefore, the observing system is stabilized because $V > 0$, $\frac{dV}{dt} < 0$ as to Lyapunov Stability Theorem.

5. Experiments

5.1 Implements

The practical implementation of the proposed observer requires the high functional signal processor for the large volume of caculations. Therefore, the obsever was implemented using a TMS320C31 32 bit DSP. The structure of the complete system is shown in Fig6. The motor is driven by a DC source IGBT converter. The position and speed observer is evaluated experimentally using a 4 phase SRM. The DSP not only computes the observer but also deals with the phase current chopping and switching pattern for the drive. The obsever was run on-line at a 130us sampling rate.

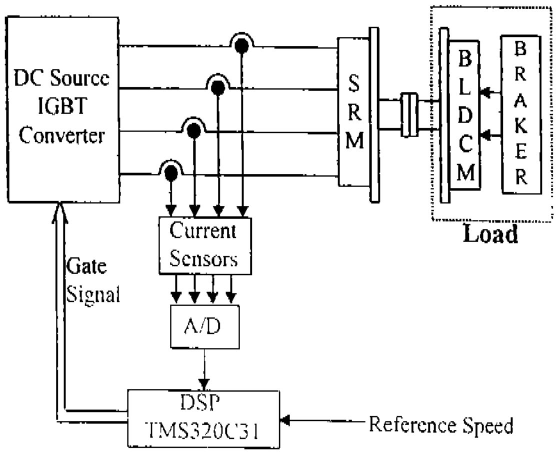


Fig6. System Block Diagram for experiments

The performance of the system realized with the equipments as shown in Fig6, in which a BLDC motor gives a square wave load torque by utilizing the braker.

Table2. shows the load ratings which is composed of the BLDC motor and braker.

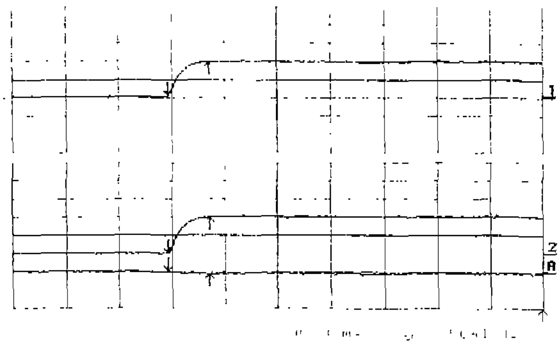
Table2. The load ratings

Stall Torque	3.8N.m	Rated Current	4.8A
Damping Coefficient	0.003	Brake Maximum Torque	3.2N.m

5.2 Results

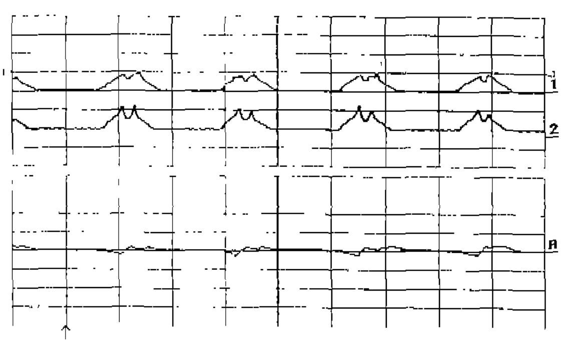
The practical estimation results are presented in Fig6,7,8,9 along with actual measurements. Fig6 shows the real speed(ch1), the estimated speed(ch2), and the estimation error(chA) in the reference speed 1000rpm and the load torque 0.4N.m. The estimation error converges to "Zero". Fig7 is Current waveform in speed reference 1000rpm. The estimation error occurs since the phase current estimation is always in transient state. Fig8 shows the real speed(ch1), the estimated speed(ch2) and esitmation speed error(chA) in the acceleration speed reference from 1000rpm to 2000rpm.

Fig8 presents the speeds(ch1,ch2), error(chA) in deceleration speed reference from 2000rpm to 1000rpm.



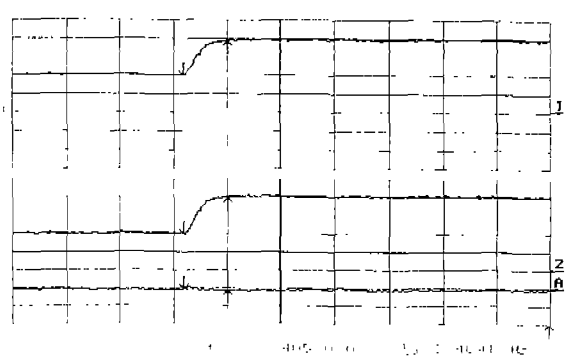
Ch1 Real Speed(500rpm/div), Ch2 Estimated Speed(500rpm/div)
ChA Estimation Speed Error(500rpm/div), 0.5sec/div

Fig6. Speed waveforms in reference speed 1000[rpm]



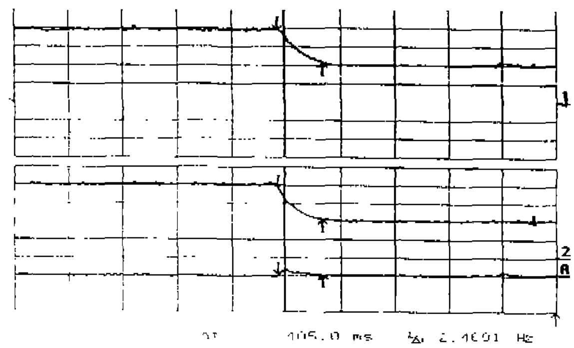
Ch1 Real Current(2[A]/div), Ch2 Estimation Current(2[A]/div)
ChA Estimation Current Error(2[A]/div), 5[ms]/div

Fig7. Current waveforms in the reference speed 1000[rpm]



Ch1 Real Speed(500rpm/div), Ch2 Estimated Speed(500rpm/div)
ChA Estimation Speed Error(250rpm/div), 0.5sec/div

Fig8. Speed waveforms in the acceleration reference speed 1000[rpm] - 2000[rpm]



Ch1 Real Speed(500rpm/div), Ch2 Estimated Speed(500rpm/div)
ChA Estimation Speed Error(500rpm/div), 0.5sec/div

Fig9. Speed waveforms in the deceleration reference speed 1000[rpm] - 2000[rpm]

This experimental results show that the observer using MRAS has the good performance

6. Conclusion

This paper introduces the new parameter estimating method using the adaptive reference model without speed or position sensors. The proposed MRAS observer shows the robust performance in a wide range of speed and even the load variation. So this method is expected to be applied in nonlinear system usefully. The validity is proved by experiments.

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