Design of Sliding Mode Observer for Switched Reluctance Motor

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ABSTRACT

Generally, a switched reluctance motor (SRM) drive requires a rotor position sensor for commutation and current control. However, this position sensor causes an increase for cost and size of motor drive. In this paper, a sliding mode observer is proposed for indirect position sensing in SRM drive. This estimated rotor position is used for the electric commutation of the machine phases. The paper includes a design approach and operating performance based on the proposed sliding mode observer.

1. INTRODUCTION

SRM has a simple rotor construction without magnets, rotor conductors, and brushes. Its simple construction makes the SRM drive an interesting alternative to compete with permanent magnet brushless DC motor and induction motor drives. However, the rotor position estimation in SRM is necessary for synchronizing the phase excitation pulse because the continuous pulse excitation source is required. Usually, an encoder, resolver or Hall sensor attached to the shaft is used to measure the rotor position. These position sensors can give a position information continuously, but they increase both cost and size of motor drive. Thus, in order to eliminate this physical position sensor, a number of indirect position sensing techniques have been proposed for SRM drive.

In this paper, a position sliding mode observer based on state estimation schemes is proposed in which load disturbances, parameter variations, and model errors between estimated and measured results have been taken into account. This sliding mode observer aims to offer the advantages of inherent robustness of parameter uncertainty and easy application to SRM drives. This technique can avoid an added diagnostic circuitry and the generation of negative torque. With the proposed technique, a sliding mode observer model can successfully estimate the rotor position based on the measured motor voltages and the difference between the estimated and measured motor currents.

2. MECHANICAL EQUATION OF SRM DRIVES

The SRM drive model is described as

$$\begin{aligned}
\frac{d\lambda}{dt} &= -\mathbf{r}\frac{1}{\mathbf{L}}(\theta)\lambda + \mathbf{V} + \mathbf{w}_{\lambda} \\
\frac{d\omega}{dt} &= \frac{T_e - T_l}{J} - \frac{B}{J}\omega = -\frac{B}{J}\omega + \frac{T_e}{J} + \omega_{\omega} \\
\frac{d\theta}{dt} &= \omega + \omega_{\theta} \\
\mathbf{i} &= \frac{1}{\mathbf{L}}(\theta)\lambda \\
T_e &= T_e(\mathbf{i}, \theta)
\end{aligned} \tag{1}$$

where $\mathbf{V} = [V_1, V_2, \ldots V_n]^T$ is the vector of terminal phase voltages, $\mathbf{i} = [i_1, i_2, \ldots i_n]^T$ is the vector of terminal phase currents, $\lambda = [\lambda_1, \lambda_2, \ldots \lambda_n]^T$ is the vector of flux-linkage, $1/\mathbf{L}(\theta) = [1/L_1, 1/L_2, \ldots 1/L_n]$ is the matrix of mutual inductances, and $\mathbf{r} = [r_1, r_2, \ldots r_n]$ is the matrix of phase resistances. In addition, ω is the rotor speed, B is the damping coefficient, J is the combined inertia of the rotor, θ is the rotor position, T_e is the electromagnetic torque, and T_l is the load torque.

Based on the system experimental parameters of a typical three-phase 6/4 SRM drive, the mutual inductance of phase a can be modeled as follows:

$$1/L_a(\theta) = 126.58 + 15.34\cos\theta \tag{2}$$

The mutual inductance of phase b and c are similarly expanded. Thus, the output current state equation is as follows:

$$\mathbf{i} = \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} = \left(\frac{1}{\mathbf{L}_0} \quad 0 \quad \mathbf{D}_0\right)(\lambda \;\; \omega \;\; \theta)^T + \mathbf{C} \tag{3}$$

where,

$$\frac{1}{\mathbf{L}_0} = \begin{pmatrix} \frac{1}{L_a(\theta)} & 0 & 0 \\ 0 & \frac{1}{L_b(\theta)} & 0 \\ 0 & 0 & \frac{1}{L_c(\theta)} \end{pmatrix}$$

$$\mathbf{C} = (C_a, C_b, C_c)^T \qquad (4)$$

$$\mathbf{D}_0 = \begin{pmatrix} -15.34 \sin\theta_0 \lambda_{a0} \\ -15.34 \sin(\theta_0 - 30^\circ)\lambda_{b0} \\ -15.34 \sin(\theta_0 + 30^\circ)\lambda_{c0} \end{pmatrix}$$

They are constant matrices.

3. MODELING OF SLIDING MODE OBSERVER

The sliding mode observer is constructed as follows:

$$\begin{aligned} \frac{d\hat{\lambda}}{dt} &= -\mathbf{r}\frac{1}{\mathbf{L}}(\hat{\theta})\hat{\lambda} + \mathbf{V} + \mathbf{K}_{\lambda}\mathrm{sgn}(\hat{\mathbf{i}}-\mathbf{i}) \\ \frac{d\hat{\omega}}{dt} &= \frac{\hat{T}_e}{J} - \frac{B}{J}\hat{\omega} + \mathbf{K}_{\omega}\mathrm{sgn}(\hat{\mathbf{i}}-\mathbf{i}) \\ \frac{d\hat{\theta}}{dt} &= \hat{\omega} + \mathbf{K}_{\theta}(\hat{\mathbf{i}}-\mathbf{i}) \\ \hat{\mathbf{i}} &= \frac{1}{\mathbf{L}}(\hat{\theta})\hat{\lambda} \\ \hat{T}_e &= T_e(\hat{\mathbf{i}},\hat{\theta}) \end{aligned} \qquad (5)$$

where $\wedge$ denotes the corresponding estimated value and $\mathbf{K}_{\lambda}, \mathbf{K}_{\omega}$ and $\mathbf{K}_{\theta}$ are switching gains. Fig. 1 shows a sliding mode observer configuration in SRM drive. The inputs of the sliding mode observer are the source line-to-line voltages supplied by the PWM converter. The estimated three-phase currents $\hat{\mathbf{i}} = (\hat{i}_a\ \hat{i}_b\ \hat{i}_c)^T$ are compared with the measured current $\mathbf{i} = (i_a\ i_b\ i_c)^T$ and the difference of these currents is fed back through the sign functions. The system errors of observer are defined as follows:

$$e_{\ddot{e}} = \hat{\ddot{e}} - \ddot{e} = (\hat{\ddot{e}}_a - \ddot{e}_a\ \ \hat{\lambda}_b - \lambda_b\ \ \hat{\lambda}_c - \lambda_c)^T \qquad (6)$$

$$e_{\omega} = \hat{\omega} - \omega \qquad (7)$$

$$e_{\theta} = \hat{\theta} - \theta \qquad (8)$$

$$\mathbf{s} = \mathbf{e}_i = \hat{\mathbf{i}} - \mathbf{i} = \mathbf{c}(\hat{\mathbf{x}} - \mathbf{x}) \qquad (9)$$

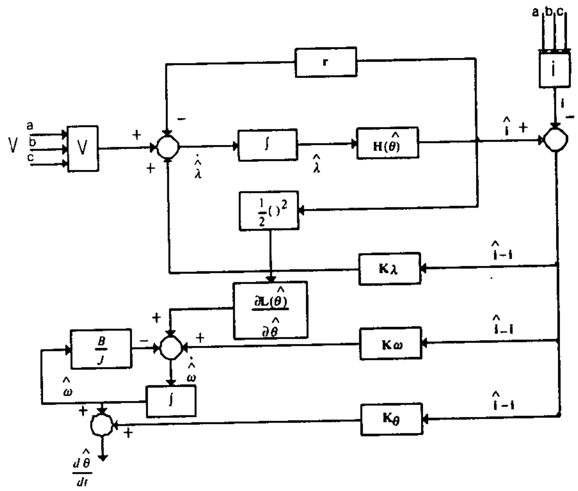

Fig. 1 Sliding mode observer configuration of SRM

From above equations, the error dynamics can be obtained as follows:

$$\begin{aligned} \frac{de_{\lambda}}{dt} &= -\mathbf{r}\cdot\mathbf{e}_i + \mathbf{K}_{\lambda}\mathrm{sgn}\mathbf{e}_i - \omega_{\lambda} \\ \frac{de_{\omega}}{dt} &= -\frac{B}{J}e_{\omega} + \frac{1}{J}(\hat{T}_e - T_e) + \mathbf{K}_{\omega}\mathrm{sgn}\mathbf{e}_i - \omega_{\omega} \\ \frac{de_{\theta}}{dt} &= e_{\omega} + \mathbf{K}_{\theta}\mathrm{sgn}e_i - \omega_{\theta} \end{aligned} \qquad (10)$$

3.1 Determination of Switching Gains $\mathbf{K}_{\lambda}$ and $\mathbf{K}_{\theta}$

The sliding surface $\mathbf{s}$ on the state output $\mathbf{i}$ and its derivative $\dot{\mathbf{s}}$ are defined as follows:

$$\begin{aligned} \mathbf{s} &= \hat{\mathbf{i}} - \mathbf{i} = (\mathbf{H}_0\ \mathbf{0}\ \mathbf{D}_0)(\hat{\lambda} - \lambda\ \ \hat{\omega} - \omega\ \ \hat{\theta} - \theta)^T \\ &= \mathbf{H}_0\mathbf{e}_{\lambda} + \mathbf{D}_0 e_{\theta} \end{aligned} \qquad (11)$$

$$\dot{\mathbf{s}} = \mathbf{H}_0\dot{\mathbf{e}}_{\lambda} + \mathbf{D}_0\dot{e}_{\theta} \qquad (12)$$

Hence, the sufficient condition of this sliding mode observer is as follows:

$$\mathbf{s}^T \cdot \dot{\mathbf{s}} = (\mathbf{H}_0\mathbf{e}_\lambda + \mathbf{D}_0 e_\theta)^T (\mathbf{H}_0 \dot{\mathbf{e}}_\lambda + \mathbf{D}_0 \dot{e}_\theta)$$

$$= \mathbf{e}_\lambda^T \mathbf{H}_0^T \mathbf{H}_0 \dot{\mathbf{e}}_\lambda + e_\theta \mathbf{D}_0^T \mathbf{H}_0 \dot{\mathbf{e}}_\lambda + \mathbf{e}_\lambda^T \mathbf{H}_0^T \mathbf{D}_0 \dot{e}_\theta + e_\theta \mathbf{D}_0^T \mathbf{D}_0 \dot{e}_\theta < 0 \quad (13)$$

From inequality (13), we can expect a sliding mode condition as follows:

$$\mathbf{e}_\lambda^T \dot{\mathbf{e}}_\lambda < 0 \quad (14)$$

$$e_\theta \dot{e}_\theta < 0 \quad (15)$$

Substitution of (6) and (10) into (14) yields

$$(\hat{\ddot{e}} - \ddot{e})(-\mathbf{r} \cdot \mathbf{e}_i + \mathbf{K}_\lambda \mathrm{sgn}\mathbf{e}_i - \omega_\lambda) < 0 \quad (16)$$

The switching gain $\mathbf{K}_\lambda$ should be chosen to be large enough to satisfy 18. However, if the gain is too large, a great amount of ripples may result, causing the estimation errors. Consequently, $\mathbf{K}_\lambda$ can be deduced from (16).

$$\mathbf{K}_\lambda < -\mathbf{r} \| \mathbf{e}_i \| - \| \omega_\lambda \| \quad (17)$$

where $\| \bullet \|$ is the quadratic norm of vector space.
Substitution of (8) and (10) into (15) yields

$$(\hat{\theta} - \theta)(e_\omega + \mathbf{K}_\theta \mathrm{sgn}\, e_i - \omega_\theta) < 0 \quad (18)$$

If $\hat{\theta} - \theta > 0$, k_θ can be deduced as follows:

$$k_\theta > e_\omega - \omega_\theta \quad (19)$$

On the contrary, if $\hat{\theta} - \theta < 0$, k_θ can be deduced as follows:

$$k_\theta > -e_\omega + \omega_\theta \quad (20)$$

From (19) and (20), gain k_θ is as follows:

$$k_\theta > |e_\omega| + |\omega_\theta| \quad (21)$$

3.2 Switching gain $\mathbf{K}_\omega$

The switching gain $\mathbf{K}_\omega$ cannot be determined from the sliding mode observer condition in direct. However, we can expect $\dot{\mathbf{s}} = \hat{\dot{\mathbf{i}}} - \dot{\mathbf{i}} = 0$ and $\dot{\mathbf{s}} = \mathbf{c}(\hat{\dot{\mathbf{x}}} - \dot{\mathbf{x}}) = \mathbf{c}\dot{\mathbf{e}}_x = 0$ on the vicinity of sliding surface. Thus, $\dot{\mathbf{e}}_\lambda$ equals zero.

$$\dot{\mathbf{e}}_\lambda = \mathbf{K}_\lambda \mathrm{sgn}(\hat{\mathbf{i}} - \mathbf{i}) - \omega_\lambda = 0 \quad (22)$$

$$\mathbf{K}_\lambda \mathrm{sgn}(\hat{\mathbf{i}} - \mathbf{i}) = \omega_\lambda \quad (23)$$

By defining $\mathbf{K}_\omega = \mathbf{L}_\omega \mathbf{K}_\lambda$ and substituting it into (10), it can be expressed as follow:

$$\dot{e}_\omega = -\frac{B}{J} e_\omega + \mathbf{L}_\omega \mathbf{K}_\lambda \mathrm{sgn}(\hat{\mathbf{i}} - \mathbf{i}) + \frac{1}{J}(\hat{T}_e - T_e) - \omega_\omega \quad (24)$$

By substituting (23) into (24), it results in

$$\dot{e}_\omega = -\frac{B}{J} e_\omega + \mathbf{L}_\omega \omega_\lambda + \frac{1}{J}(\hat{T}_e - T_e) - \omega_\omega \quad (25)$$

Defining the follow parameter:

$$\mathbf{F}\omega = \mathbf{L}_\omega \omega_\lambda + \frac{1}{J}(\hat{T}_e - T_e) - \omega_\omega \quad (26)$$

where $\mathbf{F} = (\mathbf{L}\omega\ 1)$ and $\omega = (\omega_\lambda\ \omega_\omega')$. Finally, $\mathbf{L}_\omega$ can be obtained as follows:

$$(L_{\omega a}\ L_{\omega b}\ L_{\omega c}) = \frac{\{(\omega B)^2 - (\hat{T}_e - T_e + T_l + \Delta B \omega)^2\}^{1/2}}{J} \bullet \left(\frac{1}{|\Delta r_a| \lambda_a / L_a + r_a \lambda_a / |L_a| + |\Delta r_a| \lambda_a / |L_a|}, \frac{1}{|\Delta r_b| \lambda_b / L_b + r_b \lambda_b / |L_b| + |\Delta r_b| \lambda_b / |L_b|}, \frac{1}{|\Delta r_c| \lambda_c / L_c + r_c \lambda_c / |L_c| + |\Delta r_c| \lambda_c / |L_c|}, \right) \quad (27)$$

4. EXPERIMENTAL RESULTS

The sliding mode observer model has been implemented at 1HP 6/4 SRM and PI speed controller is used for control. Fig. 2 and 3 are the estimated rotor position from sliding mode observer and measured rotor position respectively. Fig. 4 is a peed response characteristic for 1000[rpm] at no-load and Fig. 5 is a speed response characteristic at rated load. Fig. 6 shows a speed response when load variation. Fig. 7 and 8 show a speed response for change of reference speed at no-load and 300W load respectively

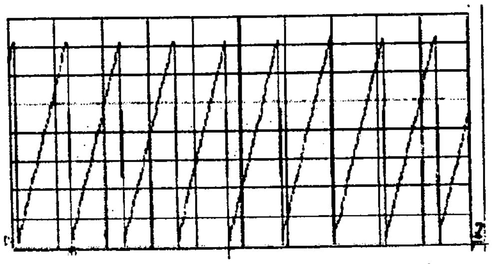

Fig. 2 Estimated rotor position angle $\hat{\theta}$

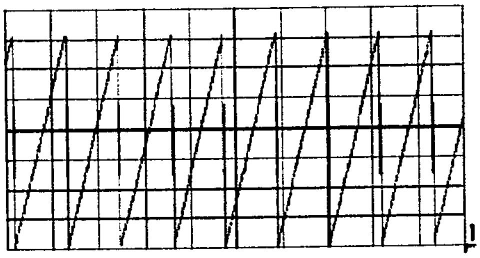

Fig. 3 Measured rotor position θ

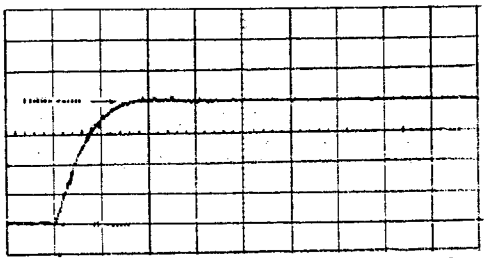

Fig. 4 Speed response characteristic for 1000[rpm] at no-load

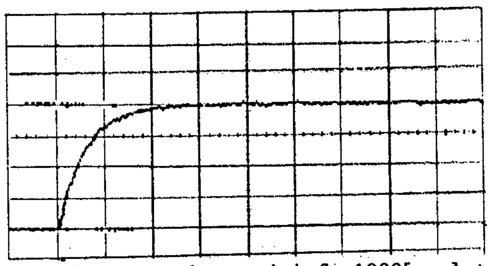

Fig. 5 Speed response characteristic for 1000[rpm] at rated load

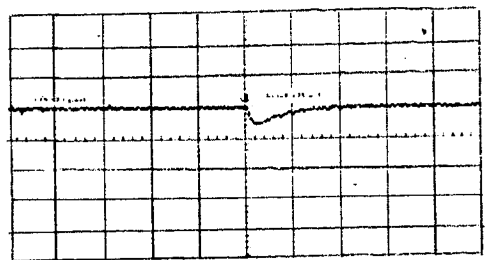

Fig. 6 Speed response characteristic for load variation at 1000[rpm]

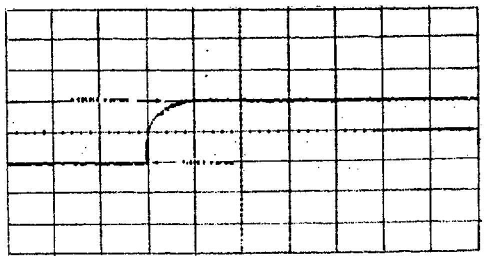

Fig. 7 Speed response characteristic for change of reference speed from 500[rpm] to 1000[rpm] at no-load

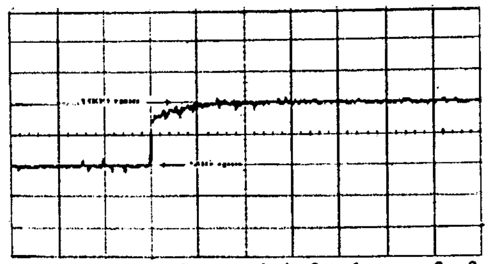

Fig. 8 Speed response characteristic for change of reference speed from 500[rpm] to 1000[rpm] at 300W load

5. CONCLUSION

This paper presents a 3-phase SRM drive using sliding mode observer. This sliding mode observer takes the place of sensor such as encorder and resolver for rotor position sensing in SRM speed control application. Experiment is implemented at load and no-load condition. From experimental result, the estimated rotor position and the stability of sliding mode observer are assured.

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