The Method of Position Sensorless Inductance Model of SRM Based on FEA

Xiaozheng Tang¹, Yidan Liu¹, Xuehua Zhao¹, Shuai Zhao²*, Mengyao Jiang², Hongzhong Ma²

¹ State Grid Jiangsu Electric Power Co., Ltd. Inspection Branch, Nanjing, Jiangsu, 211102, China
² College of Energy and Electrical Engineering, Hohai University, Nanjing, 211100, China
*635463691@qq.com

Abstract. The paper presents a position estimation method of the Switched Reluctance Motor (SRM) based on inductance model through FEA. The phase inductance of SRM is seriously nonlinear. Based on FEA, Fourier analysis result of phase inductance shows that more than three times harmonic contents are smaller. Ignoring more than three times harmonic, the simplified inductance model is expressed. Then a new rotor position estimation method is presented, which is based on the inductance model. Experiment results show that the effectiveness of the method proposed is verified, and under different saturated conditions, the method can accurately estimate the rotor position of Switched Reluctance Motor.

1. Introduction
Position estimation of SRM has received increasing attention over the last two decades to increase its reliability and reduce the overall cost of the system. Position information is crucial in SRM driver, which is mainly used to synchronize the phase sequence of current commutation. In addition, accurate location information is equally important for accurate torque control and high performance including feedback control. In order to make SR drives become viable alternative to ac drives, position estimation with wide bandwidth and high resolution turns to be a requirement.

Therefore, many scholars have proposed a lot of control methods about location estimation and sensorless control. The flux linkage and the transient current of one phase or several phases of the winding can be used to infer the rotor position. Pulse injection method has been proposed in [1]-[3]. This method is simple to be realized. But the pulse injection method reduces torque and efficiency of SRM inevitably and it is not suit for the higher speed applications. In [4]- [5], a table look-up method is used. This method requires a lot of hardware equipment and it needs to consume large amounts of memory. In [6], the phase inductances varying regularly with the rotor position were approximated by the Fourier series. Which is easy and simple, but the method of pulse injection must be used. In [8], a new method was proposed. The method calculated phase inductance based on energized phase and it overcomes the defects in [6]. In [7], a new method whose applied range is particular, only under special working condition, which is based on the inductance characteristics.

In this paper, parameter evaluation of inductance model was computed through FEA. Ignored more than three times harmonic, the simplified inductance model is expressed. Then a rotor position estimation method considering inductance saturation effects of SRM is presented.
2. Estimation and Simplification of Inductance Model

Fig.1 shows the structure of a three phase SRM used in this paper and its structure parameter are shown in Table1. The pole number of the stator and rotor is 12 and 8, respectively. The core material is oriented by silicon steel with a thickness of 0.5mm. The supply to the motor is effectively dc.

![Fig.1 The structure of 12/8 SRM](image)

The flux distribution at every part of SRM is available. The flux linkage are also computed accurately and reliably.

![Fig. 2 Inductance profile of tested SRM](image)

It can be seen from the Fig.2, the profile of the phase inductance (10 A) is approximately triangular wave, high order harmonic content of which is relatively high. As current increasing to 40A, high order harmonic content of which is relatively small. The curves can be expressed with Fourier series[^8].

\[
L = \sum_{n=0}^{\infty} L_n \cos(nN_r \theta + \psi_n) \tag{1}
\]

Where \( N_r \) is the number of rotor poles, \( L_n \) is the coefficients of Fourier series, \( \psi_n \) are the initial phases of Fourier series.

Ideally, it can be decided that all the harmonic terms must be considered in the inductance model of the machine. However, we can know higher order inductance harmonics are relatively small compared to the dominant fundamental and second inductance harmonics. Considering the first three components of the Fourier series, the simplified phase inductance model can be shown as[^8]:

\[
L_A = L_0 + L_1 \cos(\pi - \theta_{elec} + \frac{2}{3} \pi) + L_2 \cos(2\pi - \theta_{elec} + \frac{2}{3} \pi) \tag{2}
\]

\[
L_B = L_0 + L_1 \cos(\pi - \theta_{elec}) + L_2 \cos(2\pi - \theta_{elec}) \tag{3}
\]

\[
L_C = L_0 + L_1 \cos(\pi - \theta_{elec} + \frac{4}{3} \pi) + L_2 \cos(2\pi - \theta_{elec} + \frac{4}{3} \pi) \tag{4}
\]

Where \( \theta_{elec} \) is the electrical angle, \( \theta_m \) is the mechanical angle, the relationship between \( \theta_{elec} \) and \( \theta_m \) can be represented as:

\[
\theta_{elec} = N_r \theta_m \tag{5}
\]

\( L_0 \), \( L_1 \) and \( L_2 \) can be calculated from \( L_A \), \( L_B \) and \( L_C \), \( L_0 \) is the maximum inductance, \( L_m \) is the minimum inductance and \( L_m \) the middle inductance.
The three coefficients $L_0$, $L_1$ and $L_2$ can be calculated according to (6), (7) and (8).

The coefficients of polynomial is shown in the following table.

Table 1 The coefficient values of polynomial(H)

| $L_n$ | $A_0$  | $A_1$  | $A_2$  | $A_3$  | $A_4$  | $A_5$  |
|-------|--------|--------|--------|--------|--------|--------|
| $L_0$ | 0.044 7| 0.001 2| 1.25e 4| 3.28e 6| 3.48e 8| 1.24e 10|
| $L_1$ | 0.035 1| 0.002 8| 2.8e 4 | 8.84e 6| 1.23e 7 | 6.35e 10|
| $L_2$ | 0.005 2| 1.415e 4| 2.667e 5| 9.19e 7 | 1.3e 8  | 6.69e 11|

3. Principle of the inductance model

3.1. Estimation of rotor position

Considering B-phase, the following equation is given from (3).

$$2L_a\cos^2(\pi - \theta_{elec}) + L_a \cos(\pi - \theta_{elec}) + L_0 - L_B - L_2 = 0 \quad (11)$$

Cosine expressions of the electrical angle $\theta_{elec}$ can be expressed by solving the equations above as the following equation:

$$\cos(\pi - \theta_{elec}) = \frac{-L_1 \pm \sqrt{L_1^2 - 8L_2(L_0 - L_B - L_2)}}{4L_2} \quad (12)$$

In this case, because the cosine is between -1 and +1, the equation above can be simplified as next equation (13).

$$\theta_{elec} = \pi - \cos^{-1}\left(\frac{-L_1 + \sqrt{L_1^2 - 8L_2(L_0 - L_B - L_2)}}{4L_2}\right) \quad (13)$$

Table 2 The relationship between estimated position and real position

| sectors | Energized phase | Estimated position | Real position |
|---------|-----------------|--------------------|--------------|
| 5, 4, 6 | A               | $\theta_{elec} / N_r$ | $(\theta_{elec} + \frac{2}{3}\pi) / N_r$ |
| 6, 2, 3 | B               | $\theta_{elec} / N_r$ | $\theta_{elec} / N_r$ |
| 3, 1, 5 | C               | $\theta_{elec} / N_r$ | $(\theta_{elec} + \frac{2}{3}\pi) / N_r$ |

We can use $L_A$ or $L_C$ replacing of $L_B$ to get $\theta_{elec}$. The relationship between estimated position and real position is shown in Tab.2.
3.2 Sensorless control system implementation

Fig. 3 shows a block diagram of the implementation of sensorless control system used in this study. It can be seen from the figure that the bus voltage $u_{dc}$ is measured by the voltage sensor and the phase current $i$ is measured by current sensor respectively. At the same time, the three coefficients $L_0$, $L_1$, and $L_2$ of simplified inductance model for corresponding current are also estimated by putting the current into the inductance coefficients calculation module. Then the three coefficients and the inductance value calculated by the phase inductance module are put into angle calculation module together, which can calculate the rotor position angle $\hat{\theta}$ and instantaneous speed $\hat{\omega}$. The rotor position angle and speed signal will be sent to the controller module together to control the system eventually.

4. Experimental result

In this paper, the voltage drop is deducted from the phase voltage and the flux linkage is obtained by integrating the voltage difference. Fig. 6 shows the flux linkage estimation process in real-time. During excitation, the phase inductance of the excited phase is computed using the flux linkage and the phase current detected by the sensor. Finally, the rotor position $\hat{\theta}$ can be calculated by the proposed method. Chopped current control (CCC) with fixed turn-on angle $\theta_{on} = 1^\circ$ and turn off angle $\theta_{off} = 19^\circ$ is used.

Fig. 5 (a) shows experimental results under rated-load condition (load current is about 40 A). As can be seen from Fig. 5 (a), the composed inductance waveform is also an approximate saw-tooth wave. But its amplitude is decreased as the inductance is in saturation condition. Its maximum value is about 0.04H, minimum value is 0.01H. In Fig. 5 (b), the estimated position is compared with the actual rotor position. It can be noted that the rotor position is also accurately detected at rated load condition. The maxim angle error is about 0.5 degrees.
5. Conclusions
The idea of the control method implemented in this work is using simplified inductance model through FEM to estimate rotor position. A Fourier transform of phase inductance was computed. It can be concluded that higher order inductance harmonics are relatively small compared to the dominant fundamental and the second inductance harmonic. Then a rotor position estimation method considering inductance saturation effects of SRM is presented. The method takes the impact of inductance saturation into account and can get a continuous rotor position angle estimation. It is equivalently important for high performance motion and precise torque control. In the future, it will be a challenge to obtain four quadrant controllers of SRM. This is the subject of our current research.

Acknowledgments
This work is supported by State Grid Jiangsu Electric Power Company Science and Technology Project (Research on Test and State Detection Technology of Synchronous Compensator in Jiangsu Power Grid. No. J2019114) and Grant from the brain drain program 111 (B14022).

References
[1] Chen Hai Jin, Shi Long Xing, Zhong Rui, et al. A robust non-reversing starting scheme for sensorless switched reluctance motors[C]. Proceedings of IEEE Conference on Mechatronics and Automation, 2009: 2297-2301.
[2] Komatsuzaki A, Bamba T, Miki I. A position sensorless speed control for switched reluctance motor at low speeds[C]. IEEE Power Engineering Society General Meeting, 2007: 1-7

[3] Pasquesoone G, Mikail, R., Husain, I. Position Estimation at Starting and Lower Speed in Three-Phase Switched Reluctance Machines Using Pulse Injection and Two Thresholds[J]. IEEE Transactions on Industry Applications, 2011, 47(4): 1724-1731

[4] Dr. N.H. Mvungi ; Sensorless Commutation Control of Switched Reluctance Motor, World Academy of Science, Engineering and Technology 25 2007: 325-330

[5] Koblara T, Sorandaru C, Musuroi S, et al. A low voltage sensorless switched reluctance motor drive using flux linkage method[C]. International Conference on Optimization of Electrical and Electronic Equipment, 2010: 665-672.

[6] Yojiro Miura, Akitomo Komatsuzaki, Ichiro Miki. A Rotor Position Estimation of SR Motor Based on Complex Plane Expression of Phase Inductance[C]. Electrical Machines and Systems, 2009. ICEMS 2009. International Conference on , Japan, 15-18 Nov. 2009

[7] J. Cai and Z. Q. Deng, “Sensorless Control of Switched Reluctance Motors Based on Phase Inductance Model in Linear Regions,” Proceedings of the CSEE, vol. 32, pp. 114-123, May 2012.

[8] Song-Yan Kuai, Xue-Feng Li, Xing-Hong Li, and Jinyang Ma. Variable Coefficient Inductance Model-Based Four-Quadrant Sensorless Control of SRM[J]. Journal of Power Electronics, 2014, 14(6): 1243-1253.