# *Sensorless Control of Switched Reluctance Motor Drive Using an Improved Simplified Flux Linkage Model Method*

Tao Wang, Wen Ding, Yanfang Hu, Shuai Yang, Shuai Li
School of Electrical Engineering, Xi'an Jiaotong University
Xi'an, China
wangtaowa@stu.xjtu.edu.cn; wending@xjtu.edu.cn

***Abstract*—A sensorless control strategy for switched reluctance motor (SRM) drive based on an improved simplified flux linkage model method is proposed in this paper. Instead of searching look-up tables to take offline data of flux linkage, this paper uses polynomials to fit only the flux linkage of commutation position. Simulation is carried out in detail， and the feasibility of this theme is demonstrated. Experiments are also conducted to verify the simulation results by using a 6/4-pole prototype SRM as a research subject and the dSPACE as the controller. The simulation and experimental results are fairly consistent and the rotor position can be well estimated without position sensor.**

***Keywords—switched reluctance motor; sensorless control; improved simplified flux linkage method; polynomial fitting***

## I. Introduction

Switched reluctance motor (SRM) is a kind of doubly salient motor, only the stator is wired by coils while the rotor has no coils or permanent magnets [1]. Compared to other conventional AC and DC motors, SRM has simpler structure, smaller size, wider speed governing range and higher reliability [2].

Rotor position detection is of significant importance for SRM control [3]. The position data of the rotor is usually sampled via the mechanical sensor fixed on the rotor while the motor is operating, which could reduce reliability and increase costs. Also these sensors can hardly be used under some harsh environments [4]. Therefore, replacing mechanical sensor with sensorless method is widely researched.

Rotor position estimation of SRM can be divided into continuous position estimation and specified position estimation [5]. Continuous position estimation can obtain the position angle continuously by using the inherent relationship among inductance or flux linkage, current and position, including flux linkage method, incremental inductance method and idle phase excitation method. While specified position estimation obtains the position data uncontinuously by using current wave or the relationship between flux linkage and current, typically including current gradient method and simplified flux linkage method of this paper [6].

The simplified flux linkage method is suitable for the condition of medium or high speed operating and with heavy load. Because the phase current and phase voltage are not heavy enough to guarantee the accuracy of estimated flux linkage when the SRM is operating under low speed and no-load condition. The time of commutation is incorrect in this case.

This work was supported in part by the National Natural Science Foundation of China under Grant 51777161 and Grant 51477130.

## II. Principle of Simplified Flux Linkage Method

This paper uses a 6/4 SRM as the research subject. The mechanical angle between each neighboring rotor tooth is 90°. The turn-on and turn-off angle are 0° and 30° respectively, so the specified commutation position is the 30° rotor position.

### *A. Simplified flux linkage method for sensorless control*

Conventional flux linkage method for sensorless control requires lots of experimental data of flux linkage as ~~a~~ support, and these data will take plenty of memory space. However, the simplified flux linkage method needs to measure only few flux linkage curves of particular rotor position of SRM.

SRM is valid with the condition of single phase alternate conducting. It is only need be judge the position when commutation instead of measuring the position all the moment. In other words, it is only need to compare the estimated flux linkage of commutation position with real flux linkage by present current. If the former is greater than the latter, the present phase is continue to conduct, otherwise the present phase is shutdown and the next phase is conduct.

Fig. 1 shows the principle of improved simplified flux linkage method of the 6/4 SRM.

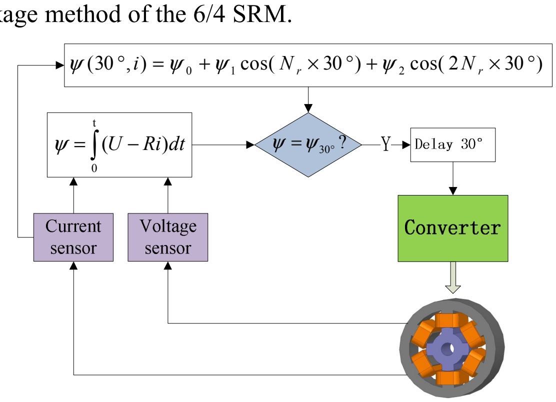



Fig. 1. Diagram of the principle of simplified flux linkage method.

Firstly, phase current and voltage are sampled by current sensor and voltage sensor and sent into the processor. Secondly the processor calculates real flux linkage and estimated flux linkage in 30° position in real-time. If the former is smaller than the latter, the converter is controlled to conduct the present phase, otherwise the present phase is shutdown and next phase is conduct. Then the pulse signal is delayed by 30° to conduct next phase.

### *B. Estimation of static flux linkage by inductance model*

In order to avoid looking up tables, this paper uses polynomials, which are deduced from linear inductance model to fit flux linkage curves of particular rotor position.

Considering the Taylor's equation of linear inductance of switched reluctance motor [7]:

$$L(i,\theta) = L_0(i) + L_1(i)\cos(N_r\theta + \pi) + \sum_{n=2}^{N} L_n(i)\cos(nN_r\theta + n\pi) \quad (1)$$

Taking the first three terms of Taylor's series is of enough accuracy:

$$L(i,\theta) = L_0(i) + L_1(i)\cos(N_r\theta) + L_2(i)\cos(2\times N_r\theta) \quad (2)$$

Then multiply current at both sides of the equation above:

$$iL(i,\theta) = iL_0(i) + iL_1(i)\cos(N_r\theta) + iL_2(i)\cos(2\times N_r\theta) \quad (3)$$

Thus, the general expression of flux linkage can be approximated as:

$$\psi(i,\theta) = \psi_0(i) + \psi_1(i)\cos(N_r\theta) + \psi_2(i)\cos(2\times N_r\theta) \quad (4)$$

Where:

$$\begin{cases} \psi_0 = \frac{1}{4}\psi_a + \frac{1}{2}\psi_m + \frac{1}{4}\psi_u \\ \psi_1 = \frac{1}{2}\psi_a - \frac{1}{2}\psi_u \\ \psi_2 = \frac{1}{4}\psi_a - \frac{1}{2}\psi_m + \frac{1}{4}\psi_u \end{cases} \quad (5) \qquad \begin{cases} \psi_a = \psi(0,i) = \sum_{n=0}^{k} a_n i^n \\ \psi_m = \psi(\frac{\pi}{2N_r}, i) = \sum_{n=0}^{k} b_n i^n \\ \psi_u = \psi(\frac{\pi}{N_r}, i) = L_u i \end{cases} \quad (6)$$

Generally, the turn-off angle is 30° for 3-phase SRM with 6/4 poles, thus:

$$\psi(30°, i) = \psi_0 + \psi_1\cos(N_r\times 30°) + \psi_2\cos(2N_r\times 30°) \quad (7)$$

The estimated phase flux linkage at commutation position is only depended on phase current. The turn-off angle is adjustable by using polynomials.

Fig. 2 shows the 3D-plot of flux linkage versus rotor position and phase current which is obtained from finite element analysis results.

Fig. 3 shows the comparison of the real flux linkage and estimated flux linkage under statics state, in which the blue lines show the real flux linkage of 45°, 22.5° and 0°, while the red lines show the estimated flux linkage estimated from the above linear inductance model. It is observed that the two curves with different positions are nearly identical so that the errors can be neglected.

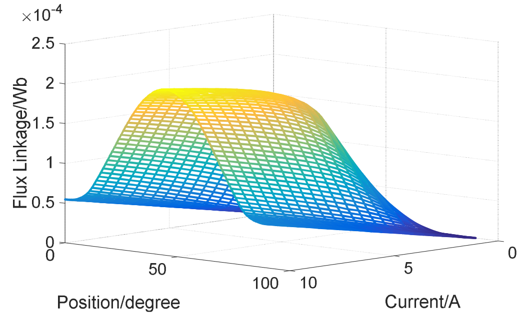



Fig. 2. 3D-plot of phase flux linkage characterisitc.

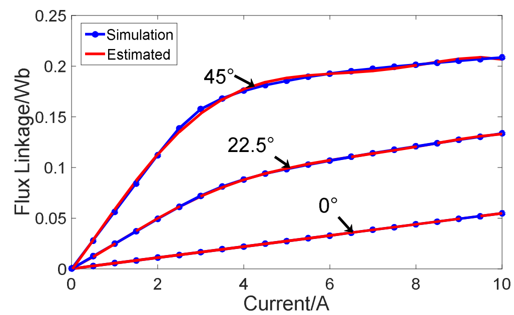



Fig. 3. Comparison of real and estimated flux linkage.

### *C. Sensorless method under current chopping control*

Fig. 4 shows the static flux linkage waveforms under current chopping control(CCC), in which the blue curve is the real-time flux linkage while the red curve is the flux linkage of 30° position. They has the only intersection point P. The real-time flux linkage between turn-on angle and 30° are all smaller than the flux linkage of 30° position, and the real-time flux linkage between 30° and turn-off angle are all larger than the flux linkage of 30° position. So the commutation position can be confirmed by testing the intersection[8].

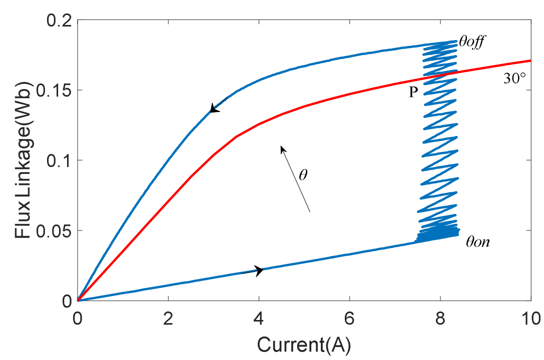


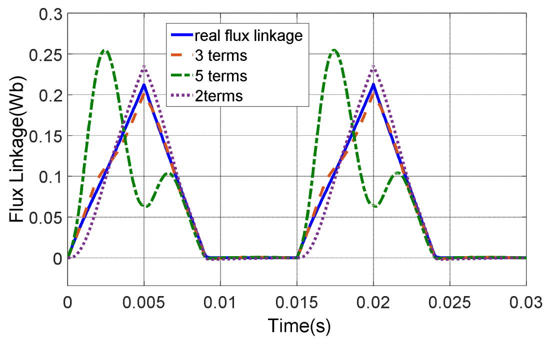

Fig. 4. Flux linkage under current chopper control.

## III. SIMULANTION RESULTS

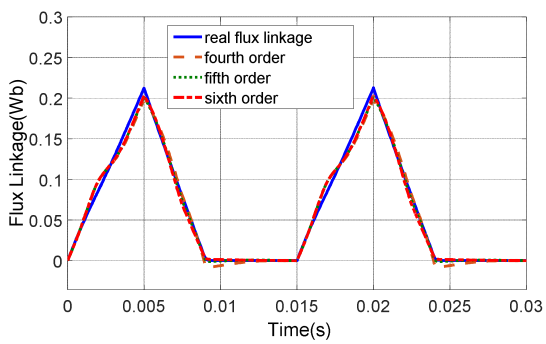
According to the above analyses of sensorless method for switched reluctance motor drive system, we can build simulation models in Matlab/Simulink environment.

In order to estimate the flux linkage in more accurate, appropriate number of terms and power of the equation should be found. The results of comparison of different number of terms and order are shown in the figures below.

Fig. 5(a) shows the estimated flux linkage of phase A by taking different terms of formula (1). Taking three terms of formula (1) is a better choice. Fig. 5(b) shows the estimated flux linkage of phase A by taking different values of k in formula (6). Different values of k (different orders) does little difference to results.




(a) Estimated flux linkage of different terms




(b) Estimated flux linkage of different orders

Fig. 5. Estimated flux linkage with different terms and orders.

## *A. Simulation results of open loop operating*

Since the simplified flux linkage method is suitable for medium and high speed operation, the speed is set to 1000rpm and 1500rpm. Since the SRM is operating on medium or high speed, the phase current is in safe range, we do not need to use CCC control.

The simulated results are shown in Figs. 6 and 7. In these simulations, load is adjusted to control the speed of the SRM. The DC bus voltage is set to 30V. Take phase A as an example.

From Fig. 6(a) and Fig. 7(a), it can be recognized that:

1) The pink curve is the estimated flux linkage, and the blue triangular curve is the real-time flux linkage. And the green curve is pulse signal of phase A(high-level means the phase is conducting).

2) The point when the estimated flux linkage is greater than the real-time flux linkage is the phase opening position, and the point when the real-time flux linkage is greater than the estimated flux linkage is the phase closing position (this point is the moment that phase current begin to follow).

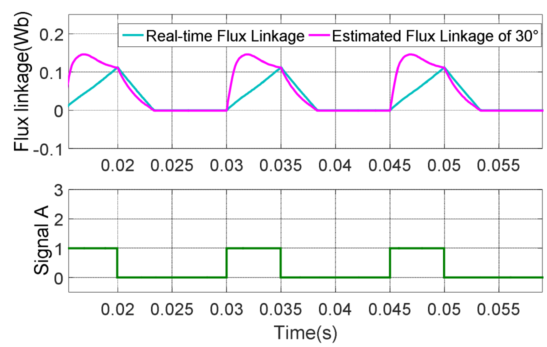
3) The pulse width of phase A is exactly one third of the whole period, which means the pulse signal that we estimated by simplified flux linkage method is the same as that from position sensor.

From Fig. 6(b) and Fig. 7(b), it can be recognized that:

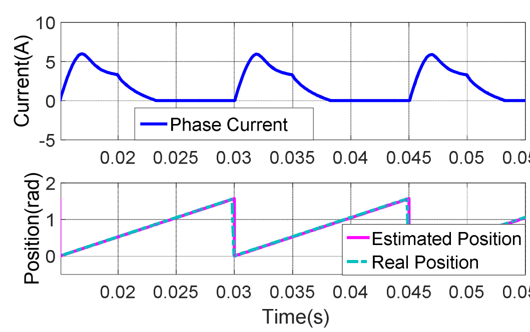
1) The blue curve is phase current. In the condition of 1000rpm: the amplitude of phase current is up to 6A. In the condition of 1500rpm: the amplitude of phase current is up to 5A.

2) The pink curve is estimated position and the blue curve is real position of phase A, and the error between them is less than 1 degree.

3) The simplified flux linkage sensorless method can estimated rotor position very well, and the error between actual commutation position and estimated commutation position can be ignored.

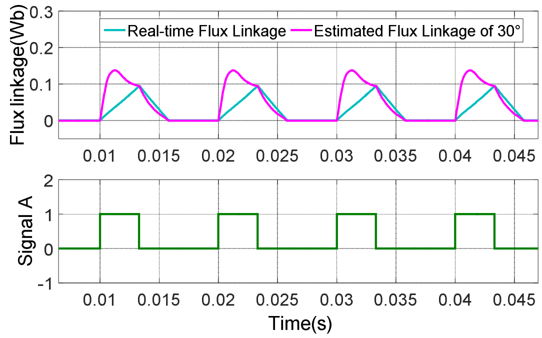



(a) Comparison of real-time and estimated flux linkage at 30°/signal state of phase A

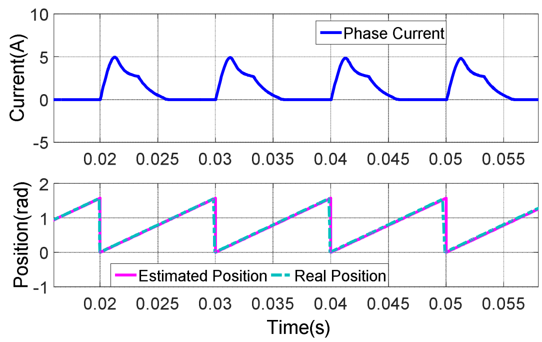



(b) Phase current/comparison of real and estimated position

Fig. 6. Simulation results of open loop opetating under $U$=30V, $n$=1000rpm, $T$=0.5N·m.




(a) Comparison of real-time and estimated flux linkage at 30°/signal state of phase A




(b) Phase current/comparison of real and estimated position

Fig. 7. Simulation results of open loop opetating under *U*=30V, *n*=1500rpm, *T*=0.3N·m

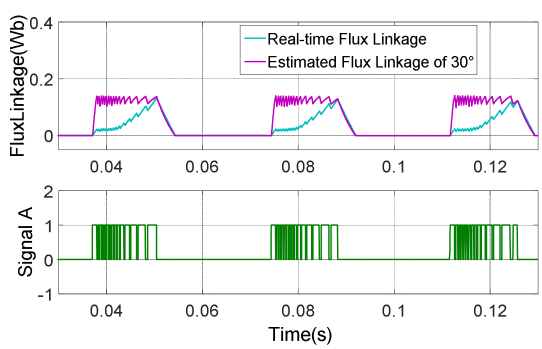
## B. *Simulation results of CCC*

Though the simplified flux linkage method is suitable for medium and high speed operation, it can still be adapted under low speed with chopper when the current is large enough.

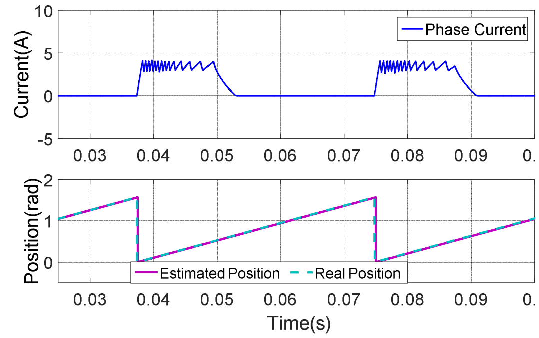
The simulation results are shown in Fig. 8. The speed is set to 400rpm, and the bus voltage is set to 30V.

From Fig. 8(a), it can be figured out that the transient real-flux linkage and the estimated flux linkage still has only one intersection.

From Fig. 8(b), it can be recognized that the real position and estimated position is nearly coincide.




(a) Comparison of real-time and estimated flux linkage at 30°/signal state of phase A




(b) Phase current/comparison of real and estimated position

Fig. 8. Simulation results of CCC under *U*=30V, *n*=400rpm, *T*=0.3N·m.

Different from the methods using a table to memory and checking the estimated flux linkage, this article introduces the linear inductance model to derive estimated flux linkage formula, which is more accurate and adjustable. The simulation results show that the simplified flux linkage sensorless method can estimate rotor position very well and can also be used with chopper.

## IV. Test and Experiment

The SRM sensorless control experimental system of this paper is mainly composed by a SRM with 3-phase and 6/4 poles, the 3-phase asymmetry half bridge power converter and the dSPACE control system. The transformer, rectifier, voltage sensor and current sensor are also included. There is no position sensor in the system. Fig. 9 shows the diagram of the sensorless control system of SRM.

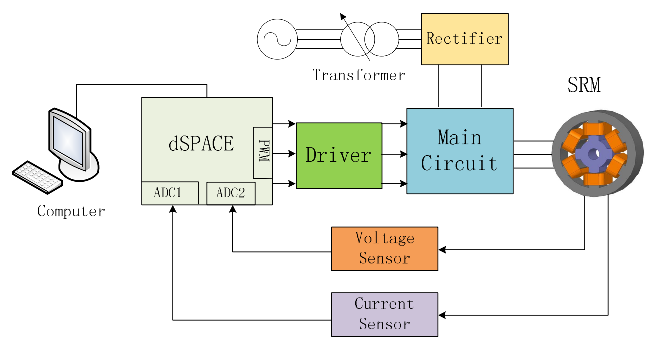



Fig. 9. Diagram of the SRM sensorless control drive system

Fig. 10 is the practicality picture of the SRM sensorless drive system. The SRM sensorless drive system mainly consists of three-phase transformer, rectifier bridge, drive and main circuit, switched reluctance motor, torque and speed measurement, DC motor, computer, dSPACE and the oscilloscope, as shown in Fig. 10.

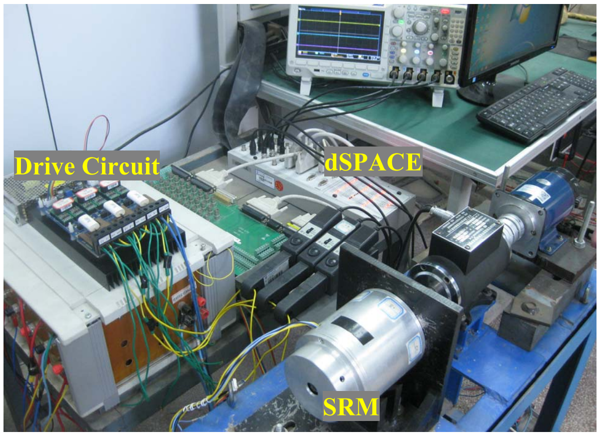



Fig. 10. Photograph of the SRM sensorless control drive system.

The topology of the 3-phase main circuit based on asymmetry half bridge converter in this paper is utilized and shown in Fig. 11. Each phase has two full controlled semiconductor devices as switches in series with the phase winding, the two switches open and close at the same time. Another two diodes are in reverse-series with the phase winding to follow current.

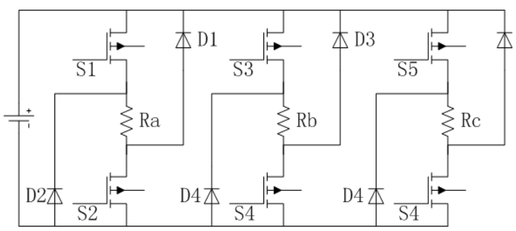



Fig. 11. Topology of the 3-phase asymmetry half bridge ciucuit.

The main circuit in this paper uses IGBT as the power semiconductor device. In order to reduce volume, miniaturized type of devices are chosen on the premise of sufficient capacity. The main circuit is detachable for convenient of repairment and replacement.

## A. *Static flux linkage measurement*

The key part to realize the simplified flux linkage method is to obtain the static flux linkage curve at particular position (45°, 22.5°, 0°). In this paper, we adopt discharge method.

According to the phase voltage equation of SRM:

$$U = Ri + \frac{d\psi}{dt} \tag{8}$$

We can obtain phase flux linkage through measuring transient phase voltage and phase current:

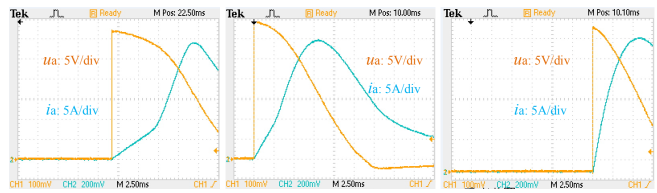
$$\psi = \int (U - Ri)dt \tag{9}$$

The static flux linkage measurement test rig consists of a DC voltage source, a capacitor, an electric relay(worked as a switch), a dividing head and the SRM.

The SRM is fixed on a flexible shelf. Firstly, a small continuous current is put into any phase (suppose phase A) of the SRM, the rotor will return to aligned position because of the reluctance torque. Then the dividing head is used to clamp the shaft. After that, turn off the switch and charge the bus capacitor, then cut the bus voltage supply and turn on the switch to release electricity into the phase winding, the change of voltage and current wave are measured by the voltage sensor and current sensor. Finally we rotate the dividing head by 22.5 degree and 45 degree to follow the above steps again.

After the data of voltage and current waveform during discharge process have been recorded, the data will be processed in Matlab to thrown up the static flux linkage curve.

Fig. 12(a)~(c) shows the phase voltage and current waveforms during the process of discharge at three particular rotor positions.




(a)Aligned position (b)Medium position (c)Unaligned position

Fig. 12. Phase voltage and current wave during the process of discharge.

Fig. 13 shows the comparison of the simulation and experiment flux linkage of 45°, 22.5° and 0°. The error between finite element simulation and experiment is acceptable.

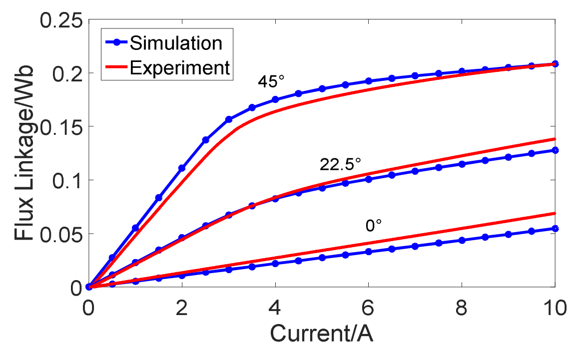



Fig. 13. Comparasion of the simulation and experiment flux linkage.

## B. *Transient experimental results*

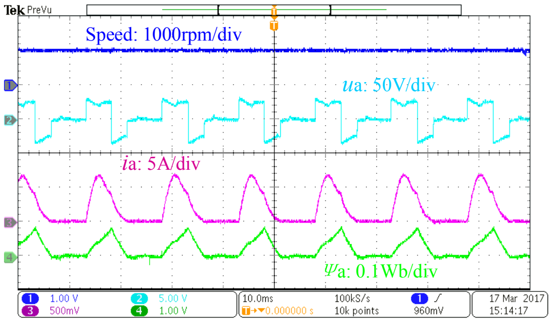
To compare with the simulation results, experimental conditions are set to correspond with simulation.

### 1) *Experimental results of open loop operating*

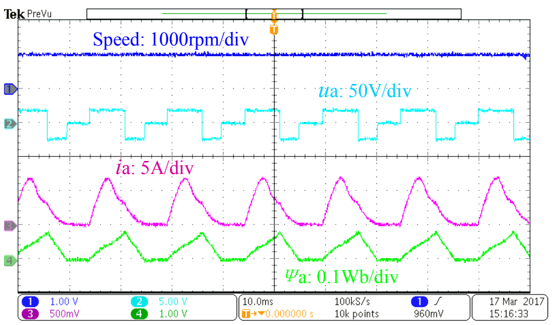
The speed is set to 1000rpm, the load is adjusted to control the speed of the SRM. The DC bus voltage is set to 30V. The turn on and turn off angle is set to 0° and 30°. Take phase A as an example, Fig. 14 shows the open-loop results.

From Fig. 14(a) and (b), it can be recognized that the phase current and phase flux linkage curve with sensorless control are the same as operating with position sensor under open loop operating. This means the SRM can be operated stable and continuously without position sensor.

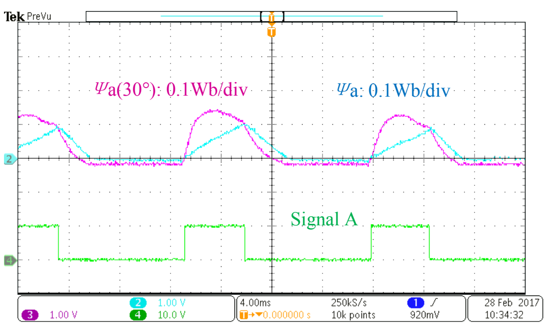
From Fig. 14(c) and (d), it can be figured out that the experimental results are in good agreement with the simulation results as shown in Fig. 6. The error between real position and the estimated position is acceptable.



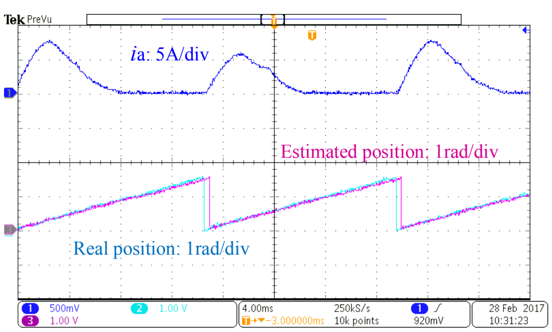

(a) Open loop operating with position sensor




(b) Open loop operating with sensorless control




(c)Comparison of real-time and estimated flux linkage at 30°/signal state of phase A



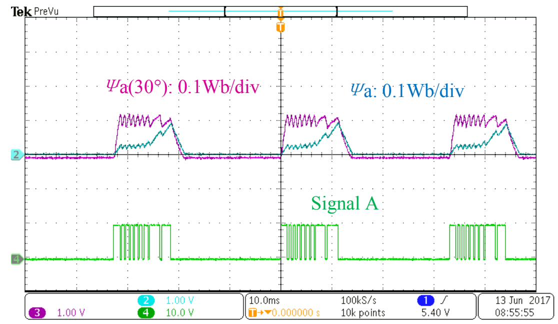

(d) Phase current/comparison of real and estimated position

Fig. 14. Experimental results of open loop opetating under $U$=30V, $n$=1000rpm, $T$=0.5N·m.

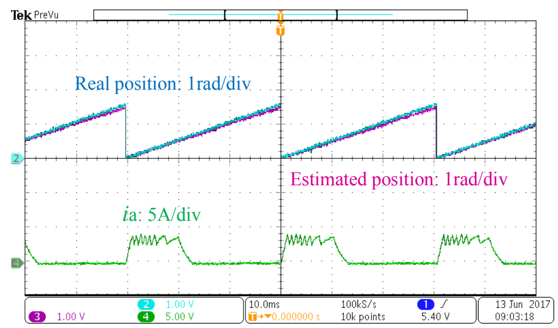
*2) Experimental results under CCC*

When it comes to sensorless current chopper control, the speed is still set to 400rpm, and the bus voltage is set to 30V.

From Fig. 15(a) and (b), it can be found out that the experimental results are corresponding with the simulated results as shown in Fig. 8(a) and(b), which means that the improved simplified flux linkage method can still be used under current chopping control.




(a) Comparison of real-time and estimated flux linkage at 30°/signal state of phase A




(b) Phase current/comparison of real and estimated position

Fig. 15. Experimental results of CCC under $U$=30V, $n$=400rpm, $T$=0.3N·m.

## V. Conclusion

The article investigates an improved simplified flux linkage method to realize sensorless control of the switched reluctance motor. Different from using a table to memory and check the estimated flux linkage, this article uses the linear inductance model to derive estimated flux linkage formula, which is more accurate and adjustable. And this sensorless method can also be used under current chopping control.

The simulation results are given out under open loop operating and current chopping control model respectively, which show that the simplified flux linkage sensorless method can estimated rotor position very well in different conditions.

A SRM with 6/4 poles is designed and manufactured to be the research subject. The experimental results are carried out under the same conditions with simulation to compare with simulation results. The fact proves that the improved simplified flux linkage method without memory any data can estimate rotor position timely and accurately.

In conclusion, the improved simplified flux linkage method which is investigated in this paper can realize sensorless control of switched reluctance motor effectively and reliably.

## REFERENCES


[1] L. Zhang, C. Liu and Y. L. Wang, “Sensorless Technology of Switched Reluctance Motor Based on the Improved Simplified Flux Method,” Electric Machines and Control, vol.17, No.11, November 2013.

[2] C. Gan, J. H. Wu and Y. H. Hu, “Online Sensorless Position Estimation for Switched Reluatance Motors Using One Current Sensor,” IEEE Trans. Power Electron. , vol. 31, No. 10, October 2016.

[3] R. G. Hu, Z. Q. Deng and J. Cai, “Sensorless Control of Switched Reluctance Motors Based on High Frquency Signal Injection,” ICEMS, pp. 3558-3563, October 2014.

[4] Y. H. Qiu, Q. H. Zhan and Z. Y. Ma, “The Indirect Position Sensing of SRM on the Basis of Simplified Flux Method ,” Proceedings of the CSEE, vol. 21, No. 10, October 2001.

[5] Z. G. Li, C. H. Li and Z. Z. Kan, “Switched Reluctance Motor Sensorless Speed Control Based on the Improved Simplified Flux Method,” Trans. CES, vol. 26, No. 6, June 2011.

[6] Z. Q. Deng, J. Cai, “Research Status and Development Trends of Sensorless Techniques of Switched Reluctance Motor,” Journal of NUAA, vol. 44, No. 5, October 2012.

[7] H. J. Zhou, W. Ding and Z. M. Yu, “A Nonlinear Model for the Switched Reluctance Motor,” ICEMS, vol. 5, pp. 568-571, 2005.

[8] H. Chen, H. Chen, “Research on the Switched Reluctance Motor Drive System for Electric Vehicles,” Xu Zhou: China University of Mining and Technology, June, 2015.