A Initial Position Sensorless for Switched Reluctance Motor Based on the Improved Pulse Injection

Lei Zhang[1,2] and Zhi Xin[1]
[1.] College of New Energy, Nanjing College of Information Technology, Nanjing, China
[2.] College of Electronic Engineering, Nanjing Xiao Zhuang University, Nanjing, China
Email: zl_srd@163.com, z_sans@163.com

***Abstract*—The algorithm of the initial rotor position estimation based on improved pulse injection method is presented for switched reluctance motor (SRM) in this paper . To implement this method, First, the division of the inductance profiles into region, the pulses are injected to the phase winding , the pulse current amplitude is set to the constant , by comparing the phase current rise time for the initial starting phase estimation . Second, based on the inductance subregional , the linear mathematical model of the phase current rise time is established for calculating the initial position angle .This method can realize the initial position estimate of SRM under standstill and inertia status ,it is quite easy to implement, the proposed method not only reduces the initial position estimation error due to improve the reliability of motor starting, and realize motor running of no inversion. The simulation and experimental results verify the correctness and feasibility of the proposed algorithm.**

***Index Terms* — switched reluctance motor; initial position estimation; phase current rise time; pulse injection**

I. Introduction

Switched reluctance motor (switch reluctance motor SRM) is a new mechanical and electrical integration of adjustable speed motor, the doubly salient structure, concentrated winding is wound on the stator, No permanent magnet material and winding on the rotor, and has the advantages of simple structure, stout, starting torque, wide speed range, high operating efficiency ,advantages[1]. The traditional photoelectric, electromagnetic and magnetic sensing type position sensor increases the cost of the system and reduce the reliability of the systems [2], limiting the application of SRM. Therefore, no position sensor technology research become the whole field is a potential direction.

SRM sensorless control method has many, in recent years, the experts of domestic and foreign have carried out extensive research on the position sensorless technique [3]. Take advantage of the signals collected by sensors , and calculate the inductance and flux linkage , and estimate the rotor position . The initial position estimation of SRM is studied [4]-[11]. The high frequency pulse is injected for each phase winding at the same time [4]-[7], the initial position is estimate d by comparison of the peak value of the pulse current, the algorithm is simple, but in the maximum and minimum area, the inductance change slightly, the peak value of pulse current variation is small, the position estimation error magnify. Based on literature [4]-[7], The robust analysis is proposed for improve the accuracy of position estimation [8], the selection of testing phase was obtained , but the algorithm is complex . The initial position estimation method is proposed by compare pulse current peak value with the current threshold [9], the method is simple and easy to implement. The initial position of the SRM is estimated by the relationship between the time of the bootstrap circuit capacitor charging current amplitude and the phase inductance [10]-[11], the capacitor selection is difficult，not to realize the control operation of the motor start. The full cycle inductance method is proposed to realize the initial position estimation, and the starting control of the no position sensor, the fault tolerance is also studied [12]. The inductance vector and orthogonal decomposition is proposed [13] , the three-phase inductance are estimated by voltage equation, the rotor initial position angle is obtained by the arctangent value based on the orthogonal decomposition .But did not discuss the arctangent value range, did not research on the method of operation on startup. The initial phase is estimated by judging the time for the phase current reach to threshold[14], the method realizes the initial position estimation under the static and rotational condition , do not realizes estimation of initial position angle. The cubic spline model is proposed by the relationship between the peak current and rotor position[15], the pulses are injected to the every phase, and the measure the peak current at the different rotor position , the mathematical model between the rotor position and current peak is established by the cubic spline , the process of the algorithm is complicated. The inductance curve is fitting by the first order Fourier series [16], and the rotor position is calculated by the voltage equation of the phase inductance, but the method does not consider the back EMF effects on position estimation.

Manuscript received July 21, 2017; revised December 1, 2017.

doi: 10.18178/joace.5.2.45-52

The purpose of this paper is to develop the rotor initial position estimate of the switched reluctance motor considering the critical problems as discussed above. In the region of the inductance curve crossing, because the current pulse response peak is relatively close, the initial position estimation error is large by comparison of pulse current peak value .Therefore, a improved pulse injected method is used for the initial position estimation in the paper, the pulse current peak is set constant, and detects the time for the phase current reach to the pulse current peak, the initial position is estimated by comparing the phase current rise time of every phase , the initial position angle is calculated by the linear mathematical model of the phase current rise time.

The proposed method solve the problems of the position estimation error in the region of the inductance curve crossing, and realizes estimation of initial position angle , no inversion operation, and is also suitable for the initial position estimation under inertia status .Finally, the simulation and experiment verify the feasibility of the proposed method .

II. Principle of SRM Sensorless

A. Basic Principle of Traditional Pulse Injection Method

The electrical dynamics of a three-phase SRM driven by a three-phase asymmetric half-bridge inverter can be described by

$$u_k = R_k i_k + L_k(\theta)\frac{di_k}{dt} + i_k\omega\frac{dL_k(\theta)}{d\theta} \tag{1}$$

where u_k is the end voltage of the phase winding, R_k is the phase resistance, i_k is the phase current , L_k is the phase inductance, ω is speed, θ is the rotor position angle , $k=1,2....,m$, m is the phase number.

At standstill, by applying high frequency and narrow pulses to the phase, the frequency of the injected pulse signal is high, the saturation effects and motional back EMF can be neglected .Therefore, the equation (1) can be simplified as

$$u_k \approx L_k(\theta)\frac{di_k}{dt} \tag{2}$$

$$L_k(\theta) \approx U_k\frac{\Delta T}{\Delta I} \tag{3}$$

According to equation (3), when the bus voltage and the injected high frequency pulse duty ratio is fixed, and the ΔT is the constant value, the phase inductance and pulse response current variation is inversely proportional.The magnitude of the pulse current ΔI is not same at different rotor position, so the initial position is estimated by comparing the magnitude of the pulse current ΔI .

B. Basic Principle of Improved Pulse Injection Method

According to equation(2), there is a quantitative mathematical relationship between the phase inductance and the impulse response current and the current rise time, the equation (3) can be deformed:

$$\Delta T \approx L_k(\theta)\frac{\Delta I}{U_k} \tag{4}$$

When the bus voltage U_k and the magnitude of the pulse current ΔI are constant value, the phase current rise time ΔT is proportional to the phase inductance L_k . The phase current rise time ΔT is not same at different rotor position for reaching to the ΔI , so by detecting the rise time ΔT of the pulse response current, the initial phase of the motor is estimated by comparing ΔT of every phase.

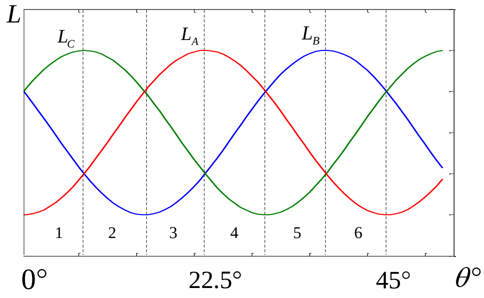


Figure 1. Inductance curve division

The inductance period is 45° for the 12/8 three phases SRM, and the division of the inductance profiles into six regions for a inductance period in Fig. 1, it shows that the phase inductance profiles and rotor position are monotone function in each partition. the phase current rise time ΔT profiles of the three phase current is same to the inductance profiles based on the equation (4) .Therefore, the division of the phase current rise time ΔT profiles into six regions, the regions is obtained by comparing the three phase ΔT , the initial starting phase is estimated for $dT/dt > 0$ in region .The logical relationship between the rise time ΔT of the three phase current and the initial starting phase is provided in Table 1. For example in the 3 region, at first ,the ΔI is set to constant value, at the same time, the high frequency pulse is injected to the three-phase, when the phase pulse current reach to the maximum variation ΔI of pulse current , the pulse current rise time ΔT is detected. $\Delta T_B < \Delta T_C \le \Delta T_A$,so the motor rotor is located in 3 region , the initial conduction phase is the B phase, as shown Fig. 2.

TABLE.1 THE LOGIC RELATION OF THE THREE MEASURE

Initial phase	**Current rise time**	**Position interval**
A	$\Delta T_A < \Delta T_B \le \Delta T_C$	$0^\circ \le \theta_A < 7.5^\circ$
A	$\Delta T_B \le \Delta T_A < \Delta T_C$	$7.5^\circ \le \theta_A < 15^\circ$
B	$\Delta T_B < \Delta T_C \le \Delta T_A$	$15^\circ \le \theta_A < 22.5^\circ$
B	$\Delta T_C \le \Delta T_B < \Delta T_A$	$22.5^\circ \le \theta_A < 30^\circ$
C	$\Delta T_C < \Delta T_A \le \Delta T_B$	$30^\circ \le \theta_A < 37.5^\circ$
C	$\Delta T_A \le \Delta T_C < \Delta T_B$	$37.5^\circ \le \theta_A < 45^\circ$

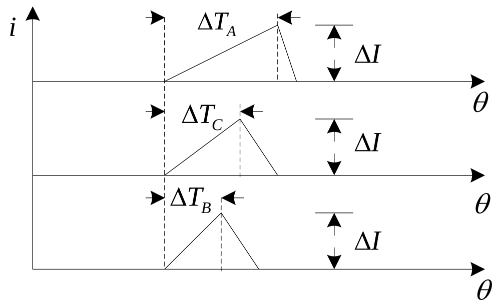


Figure 2. The pulse current rise time in 3 region

III. Analysis of Improved Pulse Injection Method

A. Comparison of Two Pulse Injection Method

In the actual process, the winding resistance and saturation effects cannot be ignored , the pulse current rise nonlinearly in Fig. 3. It shows the pulse current response waveform, the solid line shows the pulse current response waveform based on the traditional pulse injection method , $\Delta T = T_1 - T_0$, the ΔT is the constant value , based on the equation (3), the magnitude of the pulse current of the phase A and B is different($i_A > i_B$).The dotted line shows the pulse current response waveform based on the improved pulse injection method , on the basis of equation (4) , the magnitude of the pulse current ΔI are constant value, the phase current rise time of the phase A and B is different($\Delta T_B > \Delta T_A$).The values of the two phases inductance are equal approximately within the intersection region of the two phase inductance curves , the magnitudes of the pulse current are also equal approximately, hence, the degree of distinction is low, the initial position estimation error is amplified by comparison module. According to the improved pulse injection method, the pulse current amplitude ΔI is set to constant value , the pulse current of phase B continue to rise from T_1 ,and reach to ΔI at T_2 , Fig. 2 shows the pulse current curve slope of the phase B is reduced, the pulse B current rise time ΔT_B is amplified. Hence, $|\Delta T_B - \Delta T_A| > |i_A - i_B|$, increase the degree of detection of the microprocessor, improve the accuracy of initial position estimation.

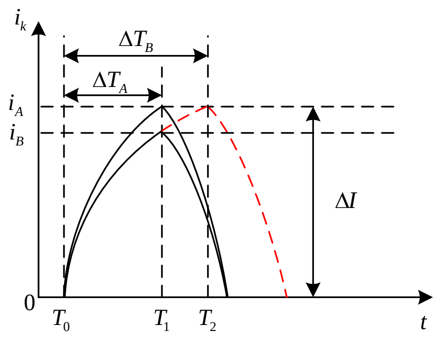


Figure 3. Schematic diagram of pulse current response

In the process of the detecting pulse current, the sampling errors may be produced， the pulse current amplitude is increased abruptly, as shown Fig. 4. It shows the diagrammatic sketch of the peak value of the pulse current, based on the traditional pulse injection method, the calculated inductance value is small according to equation (3), hence, the initial position estimation error will be amplified, the most serious consequence cause the failure of the initial partition, which ultimately leads to the failure of the motor starting, and even reverse.

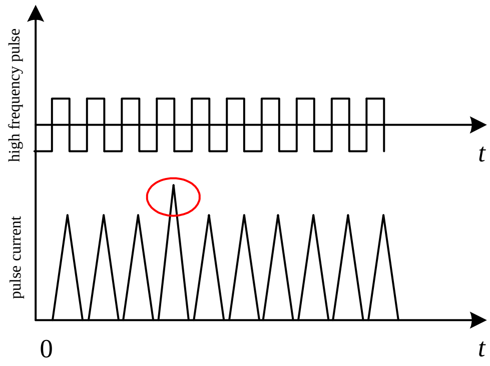


Figure 4. Pulse current error

It can avoid the occurrence of this phenomenon by using the improved pulse injection method .The amplitude of pulse current is detected real-time ,when the pulse current reaches the pulse current amplitude ΔI , the switch tube is turn off immediately，the pulse current fall ,and is in the continuous flow.

B. Adjusting of the Pulse Current Amplitude

The initial partition estimate based on the improved pulse injection method , if the pulse current amplitude ΔI is set to larger, the phase current rise time ΔT is longer, the motor run probably, and destroy the initial state of the motor, even cause the motor to reverse, the minimum value of the pulse current is determined by the current sensor. it is necessary that the detected current is in the range of the current sensor. Therefore, it is very important to select the pulse current amplitude

Ignore the saturation of the motor, the current response of the injected pulse is small, the magnetic circuit of the motor is linear, the electromagnetic torque of the phase can be given as

$$T_e \approx \frac{1}{2} i^2 \frac{dL}{d\theta} \tag{5}$$

where $\frac{dL}{d\theta}$ is the phase inductance variation slope, T_e is the electromagnetic torque, the phase inductance can be calculated by linear model, the gradient of the phase inductance can be expressed as

$$\frac{dL}{d\theta} = \frac{L_{\max} - L_{\min}}{\beta_s} \tag{6}$$

where $L_{\max}$ is the maximal value of phase inductance， $L_{\min}$ is the minimal value of phase inductance， β_s is the polar arc of motor stator.

T_L is the load torque of SRM, $i_{\max}$ is the maximum current value:

$$\Delta I = i_{\max} \tag{7}$$

At standstill, the motor do not run , so

$$T_e < T_L \tag{8}$$

From (5) and (6) and (7) and (8), the pulse current amplitude ΔI can be expressed as

$$\Delta I < \sqrt{\frac{2T_L\beta_s}{L_{\max} - L_{\min}}} \tag{9}$$

C. *Influence of Sampling Frequency*

In the course of the experiment, is necessary to analyze the error caused by the sampling frequency.

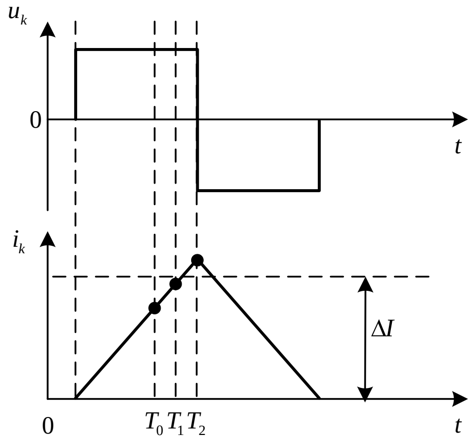


Figure 5. Sketch of error analysis

In Fig. 5, at the T1 sampling moment, the pulse current has not reached to the pulse current amplitude ΔI , the motor phase winding keep on the positive voltage, before the arrival of the next sampling period, the pulse current has reached to the pulse current amplitude ΔI . Hence ,at the next sampling T2 moment, the pulse current is higher than the pulse current amplitude ΔI ,the switch tube of the convertor is turn-off, the pulse current fall. According to above analysis, the sampling error is not greater than one sampling period based on the improved pulse injection method.

$$T_{err} < \frac{1}{f} \tag{10}$$

where f is the current sampling frequency.

IV. Position Angle Estimation

The initial region and starting phase are estimated by TABLE.1 based on the improved pulse injection method, but the initial position angle of the phase is not estimated. Hence, a mathematical model of the initial position angle is established in the paper. The phase current rise time ΔT is proportional to the phase inductance L_k , the relationship of the pulse current rise time ΔT profiles and the rotor position is shown in Fig.6, the division of the phase current rise time ΔT profiles into six regions , it was noted that there exists a fairly linear region connecting two nonlinear areas for the pulse current rise time ΔT profiles. These linear portions of the pulse current rise time profiles have been presented by the solid line between ΔT_1 and ΔT_1, the angle range of the linear region is 7.5° , the linear slope is obtained by ΔT_1 and ΔT_1, the initial position angle is calculated by the linear mathematical model precisely.

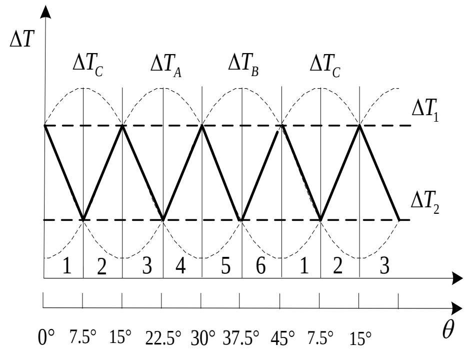


Figure 6. Linear portions of the pulse current rise time profiles

The mathematical model can be expressed as

1) Odd number region

$$\Delta T_k(\theta) = k_1(\theta - 7.5j) + \Delta T_2 \tag{11}$$

where the j is 1、3、5 , the k is the phase B、C、A

2) Even number region

$$\Delta T_k(\theta) = k_2[\theta - 7.5(j-1)] + \Delta T_2 \tag{12}$$

Where the j is 1、3、5 , the k is the phase A、B、C

The k_1 and k_2 is the slope of linear equation

1) Odd number region

$$k_1 = -\frac{\Delta T_1 - \Delta T_2}{7.5} \tag{13}$$

2) Even number region

$$k_2 = \frac{\Delta T_1 - \Delta T_2}{7.5} \tag{14}$$

Therefore, the initial position angle equation of the linear region can be expressed as

1) Odd number region

$$\theta_{est} = \frac{\Delta T_k(\theta) - T_1}{k_1} + 7.5j \quad （j = 1,3,5） \tag{15}$$

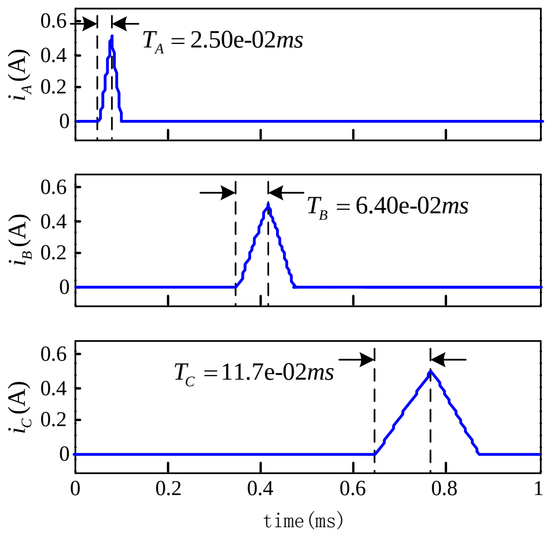
2) Even number region

$$\theta_{est} = \frac{\Delta T_k(\theta) - T_1}{k_2} + 7.5(j-1) \quad （j = 2,4,6） \tag{16}$$

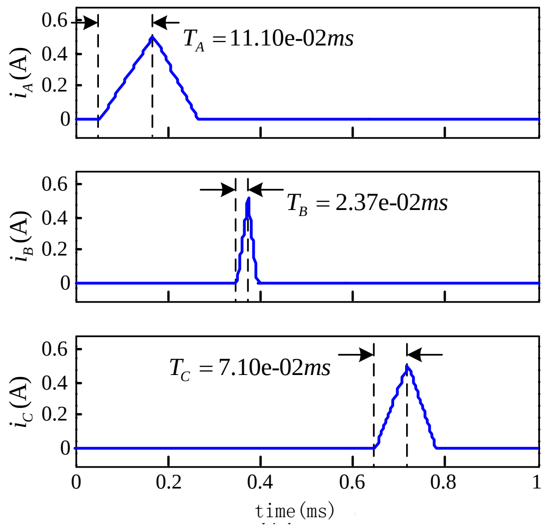
V. Simulation Analysis

In order to investigate the feasibility of the proposed method, the simulation for the improved pulse injection method was performed in the Matlb/Simulink software package. The targeted system comprises of an three-phase 12/8 SRM, the power rating1.5kW, the rated speed 1500r/min, the bus voltage 30V, the pulse current amplitude $\Delta I = 0.5\text{A}$.

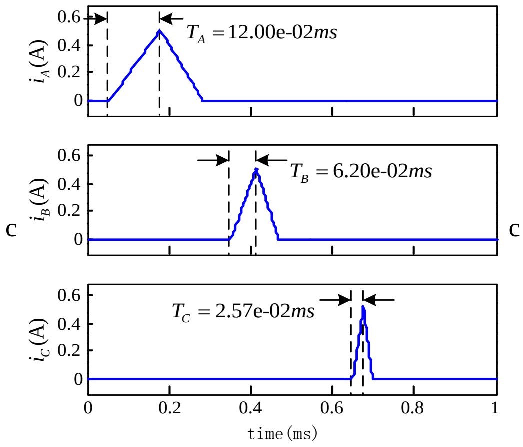
Three phase pulse current waveform are shown at the different initial positions in Fig. 7. It can seen $T_C > T_B > T_A$ in Fig. 7(a), the position of the rotor is in partition 1 ,the initial starting phase is the phase A by Table I, the initial position angle of 4 degrees is calculated by the equation (15) . $T_A < T_C < T_B$ in Fig. 7(d), lookup from Table I, it can be seen that the current rotor is in partition 6, the initial position angle of 40.5 degrees is calculated by the equation (16), the several other simulation analyses are the same.



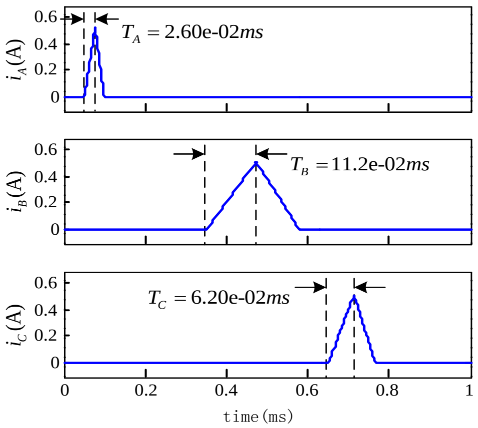
(a) The waveform of pulse current rising at the initial angle of 4 degrees



(b) The waveform of pulse current rising at the initial angle of 18 degrees



(c) The pulse current rising waveform at the initial angle of 22.5 degrees



(d) The pulse current rising waveform at the initial angle of 40.5 degrees

Figure 7. Three phase pulse current rise time at different initial positions

The inductance period is 45 degrees for 12/8 three phase SRM, the 22.5 degree symmetrical relation. Based on the improved pulse injection method, in accordance with the above simulation, the value of the phase current rise time ΔT is simulated at the different positions, the phase current rise time curve is fitted in Fig. 8.It can be seen that the curve of the pulse current rise time and the inductance curve are consistent, so as to verify the correctness of the above theory.

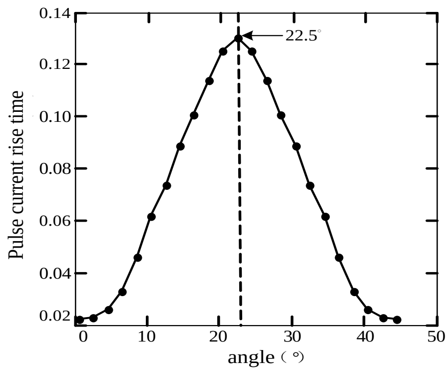


Figure 8. Relationship between the rise time and rotor position

VI. Experimental Results

The experimental setup to verify the proposed method is shown in Fig. 9.The proposed initial position estimation method has been implemented for the experimental testing on a low cost 16-bit Microchip dsPACE1104.

A: accessory power supply
B: dsPACE1104
C: control circuit
D: convertor
E:mechanical indexing
F:SRM.

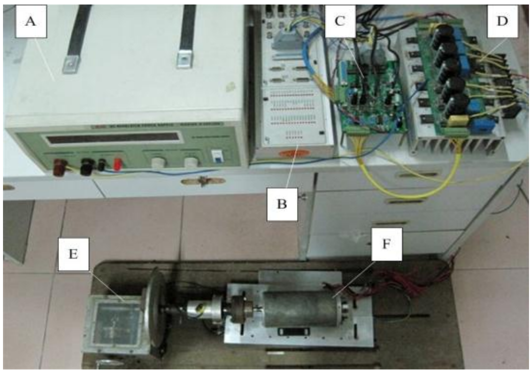


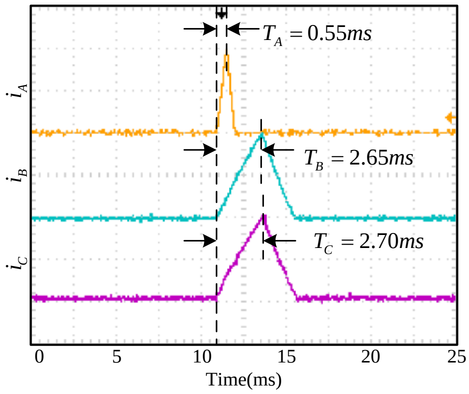
Figure 9. Experimental platform

A. Experiment at Standstill

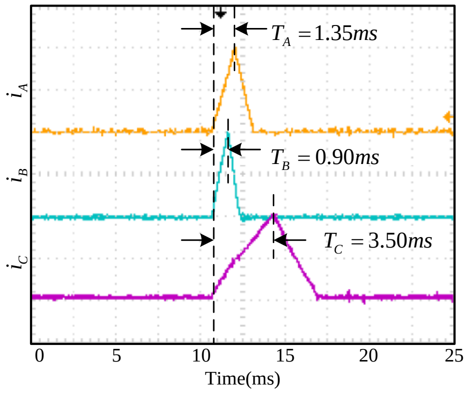
At standstill, the current amplitude ΔI is set to 1 A, the bus voltage is 30V, the high frequency pulse the pulse is injected to three phase at the same time ,the experimental result is shown in Fig.10. Fig. 10(a) shows $T_C > T_B > T_A$,we can see that the position of the rotor is in partition 1,and the initial starting phase is the phase A by TABLE.1, the initial position angle of 0.5 degrees is calculated by the equation (15). $T_B < T_A < T_C$ is seen from the Fig.10(b), and lookup from table 1, it can be seen that the position of the rotor is in partition 2, the initial starting phase is the phase A , the initial angle of 9.5 degrees is calculated by the equation (16), according to Fig.10 (a) ~ (d), with the increase of rotor position angle, the phase inductance increases, the rise time of the pulse current is also increased. The experimental results are consistent with previous theoretical analysis.

Fig.11 shows the experimental waveform based on the traditional pulse injection method. The range and the initial starting phase are estimated by comparing the pulse current amplitude of the three-phase, the testing results is presented in Fig.11(a) and Fig.11(b) at different initial rotor positions.

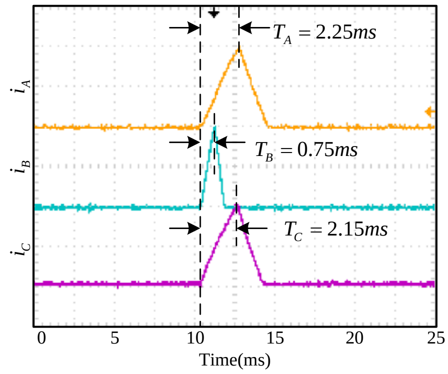
Fig.12 shows the initial position estimation error based on the improved pulse injection method and the traditional pulse injection method. The dotted line shows the initial position estimation error based on the traditional pulse injection method, the solid line shows the initial position estimation error based on the improved pulse injection method, it can seen that the estimation error is larger in the intersection region of the two phase inductance curves, and is consistent with theoretical analysis of Fig.3.



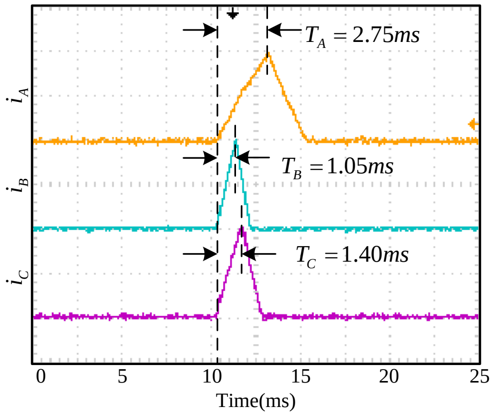
(a)The waveform of pulse current rising at the initial angle of 0.5 degrees



(b)The waveform of pulse current rising at the initial angle of 9.5 degrees

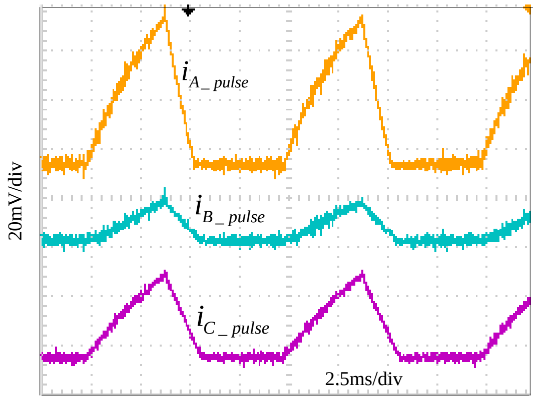


(c)The waveform of pulse current rising at the initial angle of 17.5 degrees

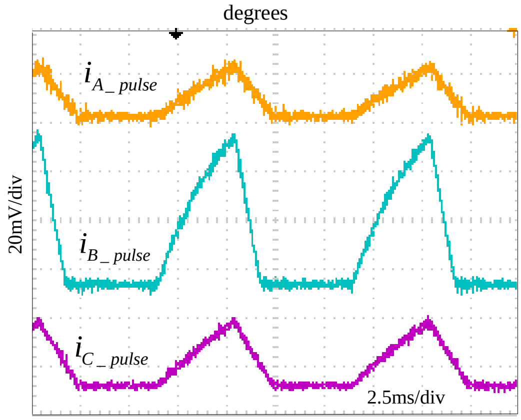


(d)The waveform of pulse current rising at the initial angle of 21.5 degrees

Figure 10. Experiment at different initial position



(a) The waveform of pulse current rising at the initial angle of 5 degrees



(c) The waveform of pulse current rising at the initial angle of 28 degrees

Figure 11. Experiment at different initial position

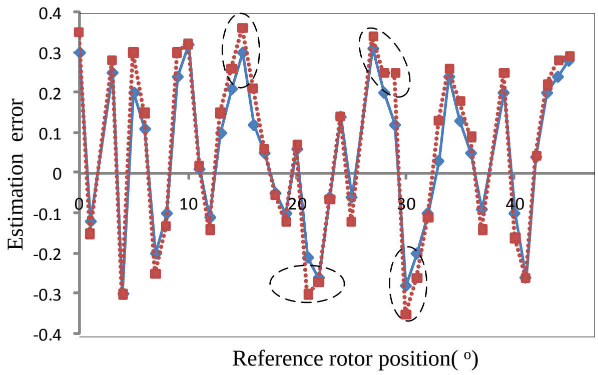
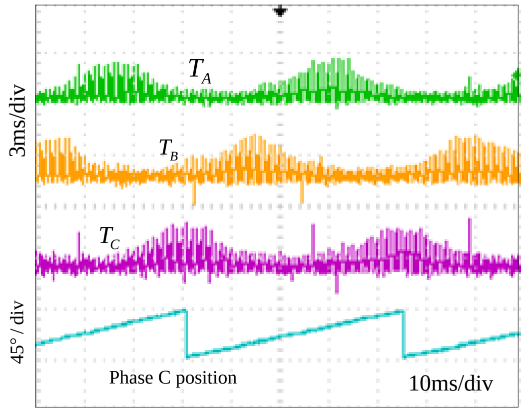


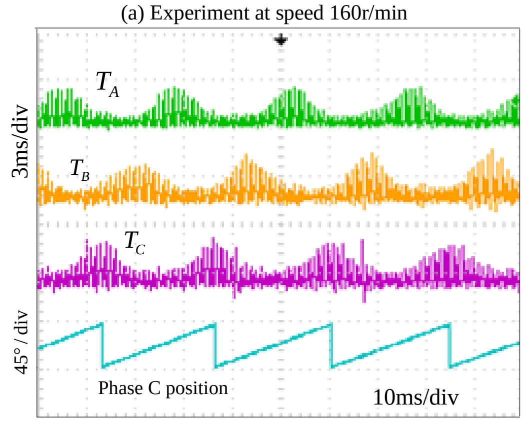
Figure 12. The initial position estimation error at two different initial rotor positions estimation model

B. Experiment at Inertia State

The method is also suitable for the initial position estimation under inertia status. The power tube of the convertor is turn off, no current on the phase winding, but the motor is running for the inertia, Fig.13 shows the experimental waveform of the initial position estimation based on the improved pulse injection method at the different inertia speed,160r/min and 350r/min, the phase current rise time (T_A、 T_B、 T_C) profiles of the three phase are same to the inductance profiles, the initial position of the phase C is estimated by comparing the three phase current rise time ,as shown in Fig.13.



(a) Experiment at speed 160r/min



(b) Experiment at speed 350r/min

Figure 13. Experiment at inertia status

VII. Conclusion

In this paper, a initial position estimation method based on the improved pulse injection method is proposed for SRM, the initial position detecting system is established. the pulse current amplitude is fixed , and detect the time of the each pulse current reaching to the preset fixed pulse current amplitude, by comparing the phase current rise time and the linear mathematical model , and estimate the initial position angles of the rotor, the position estimation accuracy is great than that of the traditional pulse injection method. The experiment platform is established based on dSPACE1104, the feasibility and validity proposed method are verified by the both simulation and experiment, the result shows a nice dynamic performance of the method. The proposed initial position estimation method is simple and suitable for without inversion. not complex operations and additional hardware circuitry.

Acknowledgment

The author would like to thank the support of the Natural Science Foundation of JiangSu. Grant No: BK20151574.

References

[1] H. X. Wu and H. Ji, T. Ni, et al. *Summary of Novel Switched Reluctance Motor Development[J]*. Micro Motors, 2011, vol. 44, no. 1, pp. 78-83.

[2] T. Per1, I. Husain, M. Elbuluk. "Design trends and trade-offs for sensorless operation of switched reluctance motor drives," in *Proc. IEEE Industry Application Conference, 13th IAS Annual Meeting*, 1995 , pp. 278-285.

[3] M. Ehsani, B. Fahimi, “Elimination of position sensors in switched reluctance motor drives: State of the art and future trends,” *IEEE Trans. on Industry Electronics*, vol. 49, no. 1, pp. 40-48, 2002.

[4] H. Gao, F. R Salmasi, and M. Ehsani, “Senorless control of SRM at standstill,” in *Proc. APEC’00*, 2000, pp. 850-856.

[5] H. W. Gao, “Sensorless control of the switched reluctance motor drive at standstill and near-zero speed,” Texas A&M University, 2001.

[6] M. Krishnamurthy, C. S. Edrington, B. Fahimi, ”Prediction of rotor position at standstill and shaft condition in switched reluctance machines,” *IEEE Transaction on Power Electronics*, vol. 21, no. 1, pp. 225-233, 2006.

[7] H. Amiri, S. Afjei E,Ataei, “A novel sensorless technique for a new field assisted switched reluctance motor,” *International Symposium on Power Electronics, Electrical Drivers, Automation and Motion*, 2008, pp. 1077-1081.

[8] W. G. Liu, S. J. Song, S. Wue, “Initial position estimation of sensorless switched reluctance motor,” in *Proc. the CESS*, vol. 29, no. 24, 2009, pp. 91-97.

[9] M. Krishnamurthy, C. C. Edrington, B. Fahimi, “Prediction of rotor position at standstill and rotating shaft conditions in switched reluctance machines,” *IEEE Trans. Power Electro*n, vol. 21, no. 1, pp. 225-233, 2006.

[10] L. Shen, J. H. Wu, and S. Y. Yang, “Initial position estimation in SRM using bootstrap circuit without predefined inductance parameters,” *IEEE Trans Power Electron,* vol. 26, no. 9, pp. 2449-2456, 2011.

[11] L. Shen, J. H. Wu, S. Y. Yang, “A novel estimation method for initial position of switched reluctance motor based on bootstrap circuit,” in *Proc. the CESS,* vol. 31, no. 6, pp. 98-102, 2011.

[12] J. Cai, Z. Q. Deng, “Sensorless control of switched reluctance motor based on full-cycle inductance method,” *Transation of China Electrotechnical Society*, vol. 28, no. 2, pp. 145-153, 2013.

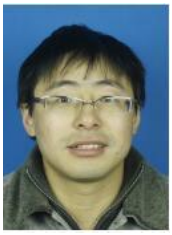
[13] T. Bamba, A. Komatsuzaki, and I. Miki, “Estimationof rotor position for switched reluctance motor at standstill,” in *Proc. PCCON07*, 2007, pp. 259-263.

[14] M. Krishnamurthy, C. C. Edrington, B. Fahimi, “Predicition of rotor position at standstill and rotating shaft conditions in switched reluctance machines,” *IEEE Trans. Power Electron*. vol. 26, no. 9, pp. 2449-2456.

[15] K. Trakrancharoungsook and S. Kittiratsacha, “Position estimation technique of a switched reluctance motor at standstill,” in *Proc. PCCON07*, 2007, pp. 264-270.

[16] A. Khalil, “Modeling and analysis of four quadrant seneorless control of a switched reluctance machines over entire speed range,” Doctoral dissertation, University of Akron ,USA.

Lei Zhang received his Ph.D. degree in Electrical engineering from College of Automation Engineering, Nanjing University of Aeronautics and Astronautics ,Nanjing, China. in Jun 2015. He has been a professor in College of New Energy ,Nanjing College of Information Technology since 2005, His current research interests include Motor control, power electronics, especially in the topics of Sensorless control for Switched reluctance motor.



Zhi Xin received his Master degree in Electrical engineering from Southeast University ,Nanjing , China. in Jun 2015. He has been a lecturer in College of New Energy, Nanjing College of Information Technology since 2005, His current research interests include Motor control, intelligent control ,power electronics power electronics.