Sensorless Control of Double-sided Linear Switched Reluctance Motor Based on Simplified Flux Linkage Method

Wenkai Wei, Qing Wang, and Rui Nie

Abstract—**The utilization of position sensor reduces the system reliability of switched reluctance motor (SRM), especially in harsh environments. It also increases the complexity of the system. Therefore, the research on sensorless control has become one of the hot spots in recent years. Comparing with the existing sensorless control technology, the new method exploring the sensorless control of double-sided linear switched reluctance motor (DLSRM) shows the following advantages:1)high accuracy , and 2) good practicability. Based on the new proposed method, the DLSRM speed controller is augmented with the peak current method and the voltage chopping closed-loop speed control. Moreover, the winding resistance in the equation is corrected according to the integral flux linkage when the phase current is zero. The accuracy and feasibility of the simplified flux linkage method in estimating the position of the DLSRM is verified.**

Index Terms—**Correct resistance value, DLSRM, sensorless, simplified flux linkage method.**

I. INTRODUCTION

L INEAR motor has the advantages of direct drive transmission, small friction loss, adjustable stroke, low noise and high efficiency, comparing with traditional rotary motor which drives the load by crank and connecting rod[1]. The double-sided linear switched reluctance motor (DLSRM) is a new type of linear motor. Furthermore, the DLSRM inherits the advantages of switched reluctance motor (SRM): double salient pole structure, mover without coil, simple and firm structure; low cost for having no permanent magnet; suitable for high temperature and harsh environment [2]. DLSRM has same operating principle as SRM, in which accurate mover position should be obtained directly or indirectly for judging the excitation and demagnetization states of every phase [3]. The method of obtaining the mover position directly is to add an additional position sensor, such as cable encoders, Holzer sensor etc. The indirect method for obtaining the mover position is based on the phase voltage and current which can provide some information about the mover position. The existence of the position sensor not only increases the

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complexity of the system, but also reduces the system reliability and the adaptation to the harsh environment. Therefore, the sensorless control has become one of the hot research topics in SRM. Some sensorless control methods have been proposed nowadays, such as injecting voltage pulse method, current gradient method, model observer method, modulation and demodulation method, flux linkage method and so on. The injecting pulse method, during the operation of switched reluctance motor, injects high-frequency voltage pulse into the non-conducting phase. The amplitude of response current pulse of non-conduction phase is inversely proportional to the phase inductance. We can determine the special position of the rotor by measuring the amplitude of response current pulse. However, if the motor rotates at high speed, the number of the injected voltage pulses is not enough to judge the present position accurately. Thus, this method is only suitable for low speed motion [4]-[5]. The current gradient method is used to determine the rotor position of the motor by detecting the change of the conducting phase current gradient. This method does not require the parameters of magnetization curves. It is suitable for all kinds of motor. And its detection precision is high. But when the motor rotates at high speed, the current has little change in the same time, so that the change of current gradient may not be detected. Therefore this method is not suitable for high speed SRM [6].This method establishes the equations of the current, phase voltage, inductance, flux linkage and resistance, and the equation of rotor position angle, angular speed and moment of inertia according to the electromagnetic characteristics of SRM. After proper simplification, the appropriate state variables, input and output variables are selected to establish the state observer, and the mover position is estimated by detecting the voltage and current of every phase. But this method has a complex system structure and requires high performance microprocessor [7]. In the modulation and demodulation method, sinusoidal excitation is applied to the non-conducting phase, to find out the position information of the motor rotor by frequency modulation, phase modulation and amplitude modulation [8]. The disadvantage of this method is that the external circuit is complex, and easy to be interfered, and also the detection accuracy is not high. The flux linkage method was proposed by J. et al for the first time [9]. This method estimates the rotor position by calculating flux linkage values and current values. The disadvantage of this method is

that a large amount of flux linkage data has to be stored, which will occupy lots of DSP storage space. Taking this shortcoming into account, [10] proposed a simplified flux method. Comparing with the original flux linkage method, the simplified flux method can reduce the amount of stored data and microprocessor's workload. But the simplified flux method can only realize single special position detection. In [2], the double position detection method based on simplified flux has been proposed. However, the above literature do not take the integral flux linkage error in the simplified flux method into account, and the error of the integral flux linkage has an important influence on the accuracy of the position estimation. To solve this problem, a new improved method based on simplified flux linkage method is presented in this paper, which can correct integral flux linkage error.
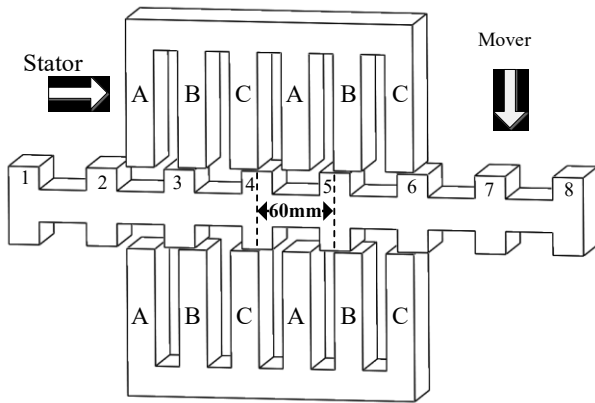
II. MOTOR STRUCTURE

Fig.1. 6/4 three phase DLSRM structure.

Fig.1 shows the structure of the 6/4 three-phase DLSRM. DLSRM is evolved from SRM. Three-phase 6/4 single linear SRM can be obtained by spreading three-phase 6/4 SRM radially. The mover of linear motor is analogous to rotor of rotary motor. Comparing with the linear switched reluctance motor, the DLSRM can counteract most of the normal force of the mover [3]. In this paper, the distance of the mover moving from one alignment position to the next alignment position is 20mm; the distance of the motor running a cycle, C-A-B-C is 60mm. For example, if the phase C is excited the C salient poles on stator will align with the fourth salient pole and the sixth salient pole on mover. Then the phase A is turned on, and the A salient poles on stator will align with the third salient pole and the fifth salient pole on mover. The mover displacement is 20mm.Then, the phase B is excited, and the mover will move another 20mm. After that, phase C is excited, and the C salient poles on stator will align with the fifth salient pole and the seventh salient pole on mover. The mover displacement is 20mm.The total distance a C-A-B-C is 60mm.

III. BASIC PRINCIPLE SIMPLIFICATION AND ALGORITHM OF FLUX LINKAGE METHOD

A. Basic Principle of Flux Linkage Method

The voltage equation of a phase winding is [10]:

$$u = ir + \frac{d\psi}{dt} \tag{1}$$

where, u is the voltage of one phase winding, i is the current of one phase winding, r is the resistance of one phase winding. $d\psi / dt$ is differential of flux linkage.

The expression of the flux linkage is deduced from (1) [10]:

$$\psi = \int_0^t (u - ir)dt + \psi(0) \tag{2}$$

We can see from the (2) that the instantaneous flux linkage can be calculated by integral of difference u and ir. The influence of mutual inductance among phases is ignored in this paper. The relationship between the flux linkage Ψ, the mover position x and the current i can be obtained:

$$\psi = \psi（x，i） \tag{3}$$

$$x = x(\psi, i) \tag{4}$$

It can be proved that the flux linkage is a single valued function of the current at any fixed position. It can be seen from (3) and (4) [10] that if the flux linkage and current are determined, the position of the mover can be known. The basic idea of flux linkage method is that the different positions have different curves of flux linkage vs current. In order to estimate the mover position, the flux linkage at the demagnetization position should be measured and stored in the controller. The data table which includes flux linkage, current and position is stored in the memory, then the estimated value of the position can be obtained according to the current and the calculated flux linkage in the actual operation.

B. Simplified Flux Linkage Method

It can be seen from the last section that flux linkage method has three main disadvantages. Firstly, the stored data in the control chip is a three-dimensional table. They take up a lot of DSP memory. Secondly, the query workload of the three-dimensional table is large. The computational complexity requires higher performance control chip which costs more. Thirdly, the three-dimensional data means that the workload of off-line measurement is very large, which reduces the practicability of the flux linkage method. In view of the above problems, [10] proposed a simplified flux linkage method. Because of the same operating principle with SRM, the control of the DLSRM can take the control experience of SRM as the reference. When the motor operates in single phase mode, it is not necessary to know the exact position of the motor, and just need to know whether the mover has reached the position where present phase needs to demagnetize or not[10]. If the demagnetization position is reached, the present phase is demagnetized and the next phase is excited. Because the flux linkage is a monotonous increasing function of the current at a fixed position . When the current is same, the corresponding flux linkage values are different at different positions. Therefore, it just needs to compare the calculated flux linkage value with the stored magnetic flux linkage data. If calculated flux linkage value is bigger than the value of the stored magnetic flux, the mover has reached the demagnetization position. The present phase should be demagnetized and the

next phase will be excited. Otherwise, the present phase will not be demagnetized. In this case, just a two-dimensional data which includes flux linkage values and corresponding current values at the demagnetization position needs to be stored in the controller. In this way, the storage space is much saved and the time for checking table is shortened. This is the basic idea of simplified flux linkage method. In addition, under the same current, the position which has the maximum inductance has the maximum flux linkage value. Because the demagnetization position of the motor is close to the maximum inductance position. The magnetization curves of different positions have similar trend [10]. Therefore, just the magnetization curve at the position which has the biggest inductance value is stored in controller. In practical application, the flux linkage value multiplies a coefficient K and its calculation result is compared with the stored magnetic flux linkage data. Thus, modifying the coefficient K can change the demagnetization position.

C. Integral Flux Error Correction

As we can see from the (5) that voltage, current and resistance affect the accuracy of flux linkage integral calculation. Voltage and current signals are detected by the Holzer sensor. They are converted into digital signals by the A/D module of the DSP. The sampling precision of the voltage and current depends on the accuracy of the Holzer sensor and the precision of the DSP. The better precision of the DSP can be obtained by the pre correction of A/D module. Another problem which arises here is that the winding resistance will change with temperature. It affects the accuracy of the flux linkage integral, especially in low speed control. Therefore, it is necessary to adjust internal   winding resistance. Due to the complex electromagnetic characteristics of SRM, the winding resistance is not equal to ratio of voltage to current, and the internal resistance cannot be obtained directly. It can be seen from the formula (1) that after the phase is demagnetized, and the integral flux linkage values also should be 0Wb when the current value is reduced to 0A[11].However, the actual flux linkage value is not 0Wbbecause the stored resistance are different from the actual resistance. The feedback regulator is used to correct the resistance of the winding until that the integral flux linkage value is 0Wb when the current is 0A. The principle schematic of resistance correction regulator is shown in Fig. 2.

IV.   STARTING OPERATION AND OFF-LINE DATA MEASURE

A. Starting Operation

In this paper, the peak current method is used to start the motor. This start-up phase estimation method is proposed by Gao who comes from University of Texas[12]. After every phase of the motor is conducted for the same short time, the phase which has the smallest inductance will have the maximum current peak value. Therefore, after phases are conducted for a short time, the phase which has the maximum current peak value continues to conduct, other phases are demagnetized. DSP starts to calculate the flux linkage of the conducting phase. However, when the current is small, the stored flux linkage is

too small so that the calculated flux linkage error is large. The error would lead to some wrong judgments. Therefore, a current threshold is set in the program. When the current is less than the threshold, the comparison of the calculated results with the reference flux linkage is invalid. It is worth noting that the current threshold should not be too large, otherwise the next phase will not be excited. The flow chart of the motor starting operation is shown in Fig. 3.
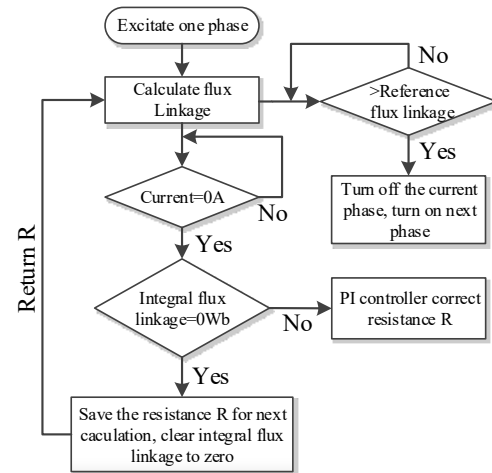

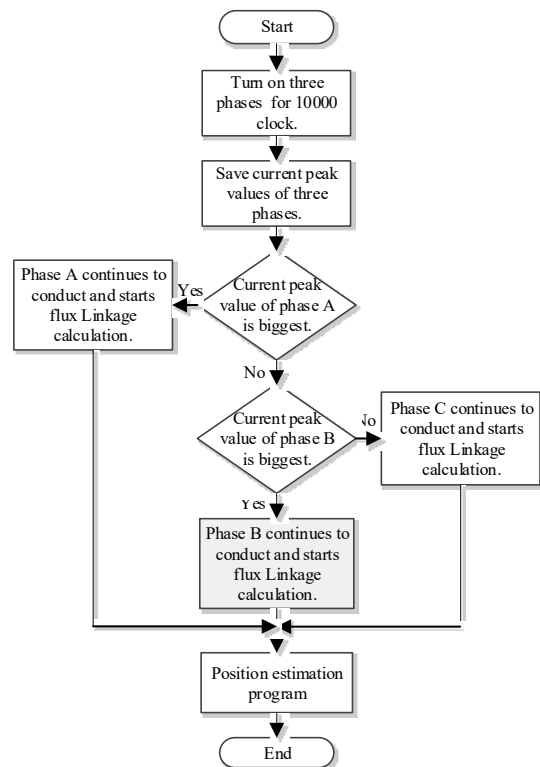Fig. 2. Flow chart of resistance correction regulator.

Fig.3. Flow chart of starting operation procedure.

B. Off-line Data Measure

Because of limitation of the motor manufacturing process, there are some differences among phases. Thus, the off-line data of every phase should be measured. Off-line measurement process of phase A is taken as the example in this paper. 12V voltage is applied to the phase A. The mover moves to the

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alignment position under electromagnetic thrust. Then 24V step voltage is applied to the phase A. The winding voltage and the current signal converted by the Holzer current sensor of phase A are captured and saved by an oscilloscope which is shown in Fig. 4.
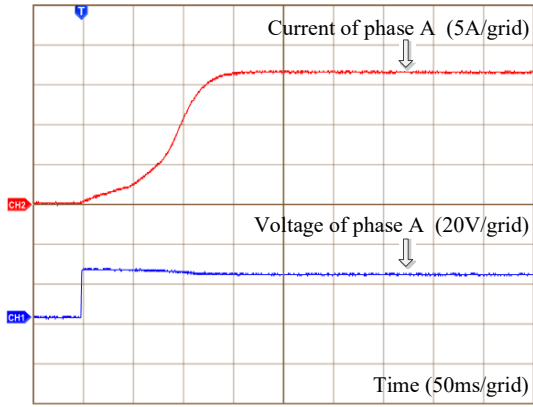

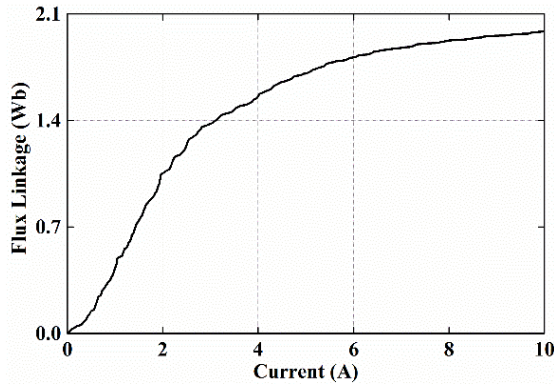Fig.4. Voltage-current test curve at the maximum inductance position of phase A.

Fig. 5. Flux linkage vs current curve at the maximum inductance position of phase A.

The collected data is processed to flux linkage vs current waveform, which is pre-stored in DSP, as shown in Fig. 5.

C. Algorithm Implementation

DSP28335 is used as the core controller in the hardware platform. The (2) must be discretized when the flux linkage is calculated. The(2) can be discretized as[10]:

$$\psi_j = \psi(0) + \sum_{k=1}^{N}[u(k) - i_j r(k)] \cdot T \qquad (5)$$

T is the sampling time interval. In this paper, current and voltage are sampled by the A/D module of DSP. T is the reciprocal of the sampling frequency of A/D. The sampling interval can be adjusted by changing sampling frequency of A/D module. $u(k)$, i_j, $r(k)$ is winding voltage, current and resistance during the K th sampling period respectively.
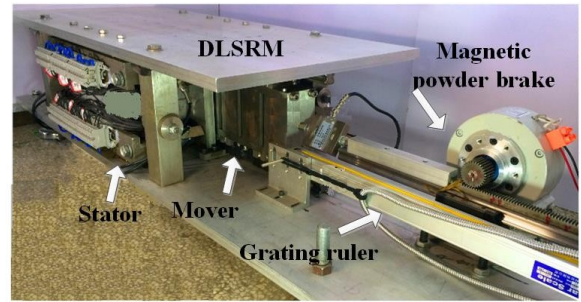
D. Experiment Platform

The experimental platform used in this paper is shown in Fig.6.

The response time of voltage sensor and current sensor used in this paper is 40us.They can meet the measurement requirements of voltage chopping frequency below 1kHZ. The controller DSP28335 has an A/D module which can sample

voltage signal and current signal at the same time. The time of DSP executing a single cycle instruction is 6.67ns. The load is supplied by the magnetic particle brake in the Fig. 6(b).The value of magnetic particle brake current multiplying 100 is the actual value of load.
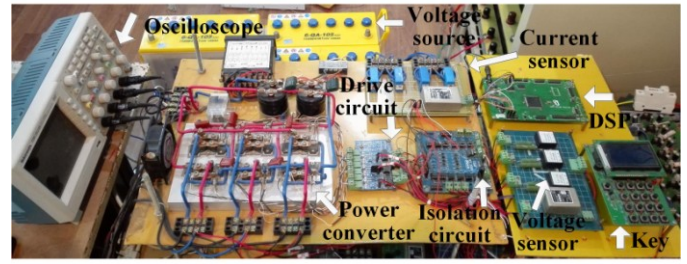
(a) Control platform

(b) Double-sided linear switched reluctance motor

Fig. 6. Experiment platform.

V. EXPERIMENTAL RESULTS AND ANALYSIS

A. Influence of The Coefficient on The Demagnetization Position Without Position Sensor

In this paper, the bus voltage is 24V. In order to facilitate the observation and comparison, the grating ruler is combined with the program to record the excitation position and demagnetization position in the experiments.

TABLE I
THE DEMAGNETIZATION POSITION OF DIFFERENT COEFFICIENT

Turn off Position (mm) / Coefficient \ Align Position (mm)	25	45	65	85	105	125
K=1	22	40	61	83	100	121
K=0.9	19	38	59	79	98	119
K=0.8	15	35	54	75	95	114
K=0.7	10	31	51	69	90	109

The mover starts from the same position every time in order to facilitate comparison. The position is randomly selected, and is recorded as 0mm. The alignment position of phase C is located at 5mm through the measurement by grating ruler. The 25mm in table is the maximum inductance position of phase A; 45mm is the maximum inductance position of phase B; 65mm is the maximum inductance position of phase C. The adjustment of coefficient K can only change the demagnetization position. It can not determine the exact demagnetization position. Therefore, the grating ruler is used to record the exact demagnetization position in this paper. It can be seen from Table I that the magnetic circuit is easy to be saturated at the position which has maximum inductance and

smallest magnetic reluctance. The relationship between the flux linkage and current is nonlinear at alignment position. The comparison between calculated flux linkage with reference flux linkages more prone to judge wrongly. The motor can not be demagnetized at the alignment position even if the coefficient K is 1. However, when the coefficient K is constant, especially the coefficient is less than 0.9, we found that the demagnetization position just has a very small fluctuation after repeated experiments. The results show that the simplified flux linkage method is accurate in position estimation of DLSRM when the coefficient is less than 0.9. The coefficient K can determine the demagnetization position of each phase in a certain range.

B.   Speed Estimation

The accuracy of speed estimation is mainly based on the accuracy of the estimated position information. Because of the saturation of the magnetic circuit at alignment position, the smaller coefficient K is selected. The chosen coefficient K is 0.8 in this paper. We found that the demagnetization position is at the distance 10mm away from the alignment position after a number of experiments in the case of load is zero. The distance between the present demagnetization position and the next demagnetization position is 20mm. Therefore, the 32 bit timer module of DSP loads the maximum value 4294967295 (DSP28335 clock frequency is 150MHZ, and it will spend 28.3sbefore timer value reduce to 0). Once any phase is conducted, the timer starts to count. The timer stops at the next demagnetization position. Speed can be calculated according to the distance and the time. The motor is seen as a uniform motion in this 20mm displacement because there is only one estimated time in this 20mm. Fig. 7 shows the comparison between the estimated speed with the calculated speed by ruler grating when the load is zero.
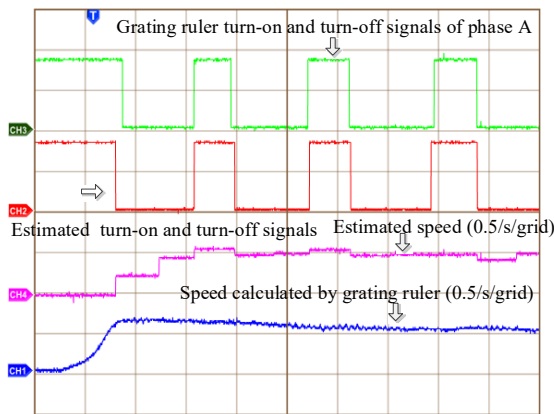

Fig. 7. Comparison of estimated speed with actual speed when the load is zero.

As can be seen from Fig. 7, Comparing with the actual position, the position estimation accuracy is high. The average speed is small and the estimation error of the speed is large in the starting period. Because the speed estimation highlights the average speed of the previous period . The injecting voltage pulse method is the main method to estimate position of low speed SRM. But [3] has found that position estimation error reaches 5.27mm when the speed is 0.45m/s, and it means that the speed estimation error will reaches 20.8% in this condition.

When the speed is greater, the error is more obvious and the motor can not even work stably. As we can see from the Fig. 7 when the mover speed is relatively stable, although the estimated speed is not a smooth curve just like the speed calculated by the grating ruler and it changes jumpily, the speed estimation accuracy is still relatively high and its volatility is small. The speed estimation is accurate if the position estimation is accurate because the calculated time is accurate.

C.   Resistance Modification

The 2.2 section has described the method which is used to correct the resistance. If the integral flux linkage value is greater than 0Wb when the current reduces to 0A, DSP program increases the value of resistance; otherwise, DSP program reduces the value of resistance. The resistance will be corrected until the integral flux linkage value is 0Wb when the current is 0 A. Fig. 8 is the comparison between the estimated excitation and demagnetization signals with the signals got from grating ruler when the load is zero.
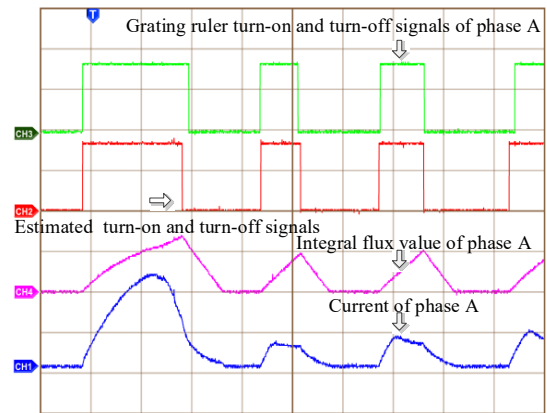

Fig. 8. Sensorless operation under the condition of resistance value correction when the load is zero.

Fig. 8 shows that the controller adjusts the winding resistance value when the phase current is 0A. The deviation of estimated demagnetization position is very small compared with the actual position. The following Fig. 9 shows that we deliberately make the initial resistance value of winding in the integral equation bigger than actual value, then the winding resistance value is corrected in the program during motor operation.
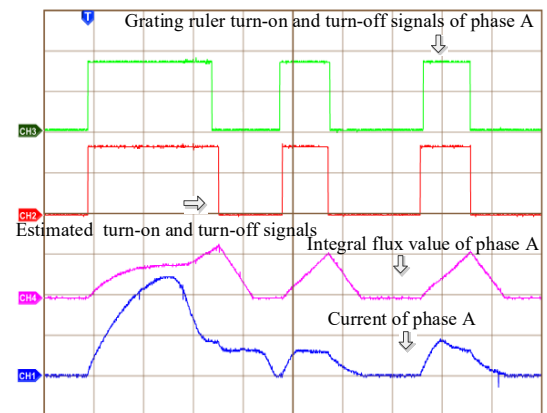

Fig. 9. Sensorless operation with correction of resistance value when the load is zero.

Fig. 9 shows that the integral value of flux linkage increases slowly due to the big initial resistance value, and the first demagnetization signal is postponed than the normal signal. After the resistance correction, it can be seen that the second and the third estimation excitation and demagnetization signals are both close to the ruler grating signals.

In order to collect more information, this paper uses two oscilloscope to collect waveform at the same time. Fig.10 shows some waveform of the control signals, flux linkage, and current of phase A, estimated speed and actual speed with the load of 10N under the proposed sensorless control in this paper.
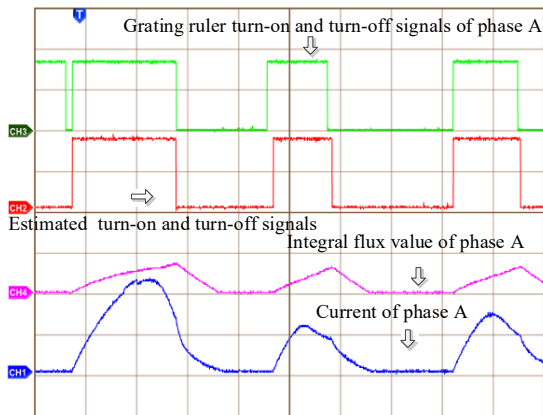
(a) Waveform of integral flux linkage value and current of phase A when load is 10N.
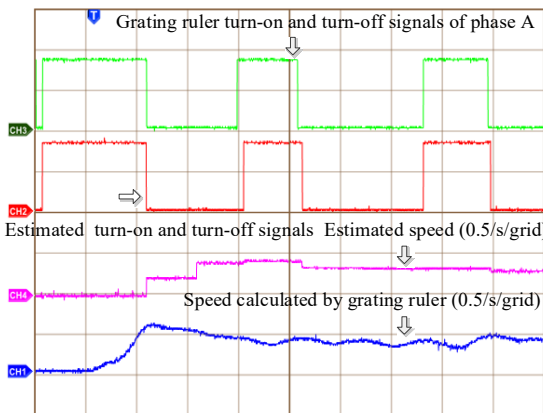
(b) Demagnetization signal and waveform of speed when load is 10N.

Fig. 10. Waveform under sensorless control when load is 10N.

When the load is 10N, the speed of the motor is less than the operation speed without any load. We can see that the accuracy of the estimated excitation and demagnetization signals is nearly the same from Fig. 10 and Fig. 7. Thus the results show that the position estimation with resistance value correction has higher precision with different speed and load.

D. Voltage Chopping Closed-loop Speed Regulation

DLSRM is a low speed motor whose speed is always less than 1.5m/s. Therefore it is suitable for DLSRM to use voltage chopping closed-loop speed regulation with fixed excitation position and demagnetization position [13]. Fig. 11 shows the operation state of DLSRM when load is 30N. Its fixed

coefficient K value is 0.8 and target speed of closed-loop speed regulation is 0.5m/s. We can see from the Fig. 11 that the accuracy of the excitation position and demagnetization position is still high under the voltage chopping speed regulation.
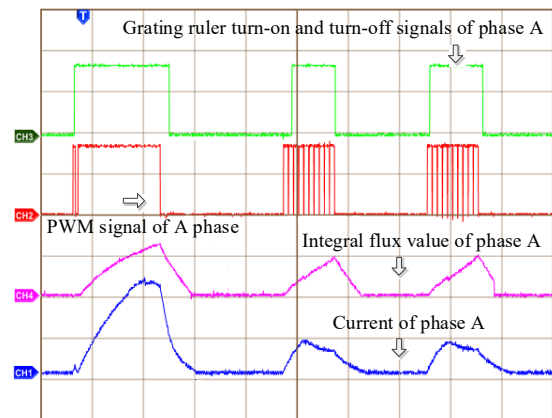
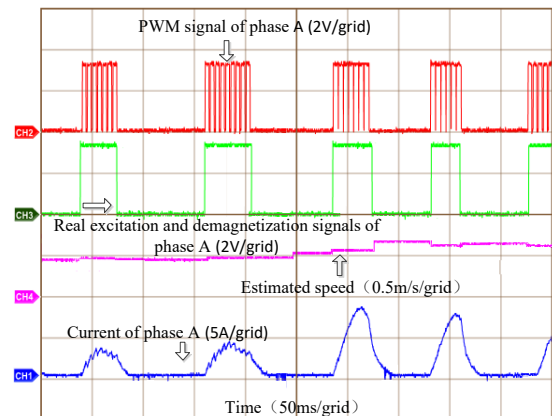(a) Waveform of integral flux linkage value and current of phase A when load is 10N.
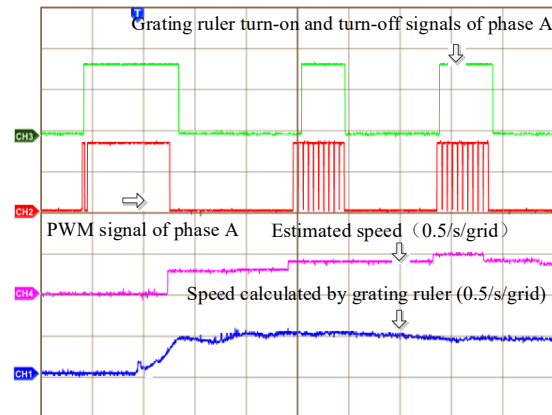
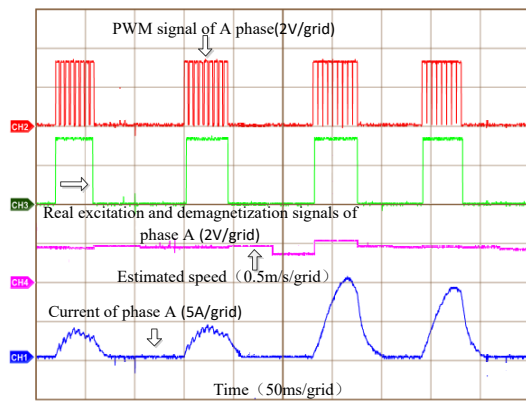(b) Waveform of PWM signals of phase A and motor speed.

Fig. 11. Closed-loop speed regulation with target speed is 0.5m/s when the load 30N.

E. Dynamic Performance

The dynamic performance of this method is shown in Fig.12.

(a) Waveform of current and speed in the case of target speed is changed when load is 10N.

(b) Waveform of current and speed in the case of load is changed when target speed is 0.5m/s.

Fig. 12. Waveform of speed and current in the case of target speed and load is variable.

As we can see from the Fig.12(a) that target speed is changed from 0.5m/s to 0.6m/s during the operation. The PWM duty increases with the increase of target speed to realize speed regulation. Waveform in the Fig.12(b) shows that the load is increased from 10N to 30N when the target speed is 0.5m/s. After increasing the load of mover, the PWM duty increases to keep the speed constant and the current increases at the same time .Waveform in the Fig.12 indicates that the accuracy of the excitation position and demagnetization position is still high in the case of target speed and load are variable.

F. Error Analysis

Error time of demagnetization signal multiplies speed is error of demagnetization position. Error time of demagnetization signal is average value of each demagnetization error time which is showed in Fig.13(a). Fig.13(b) shows that the error is about in 1.6mm. The error is due to microprocessor integration error. Moreover, the greater the speed, the smaller the error . Because the integration time is short when the speed is big . The injecting voltage pulse method is the main method to estimate position of low speed SRM. But [3] has found that position estimation error reaches 5.27mm when the speed is 0.45m/s, and it means that the speed estimation error will reaches 20.8% in this condition. When the speed is greater, the error is more obvious and the motor can not even work stably. As we can see from the Fig. 12 when the
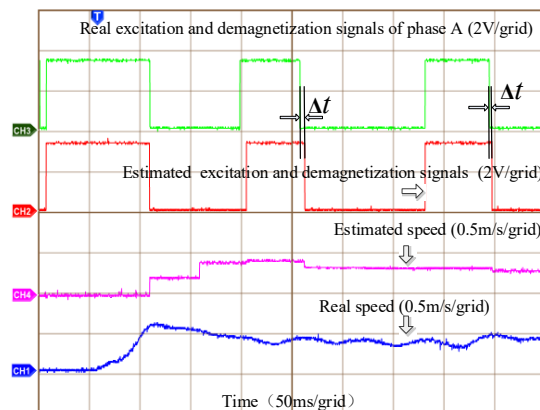
(a) Error time of demagnetization position signal
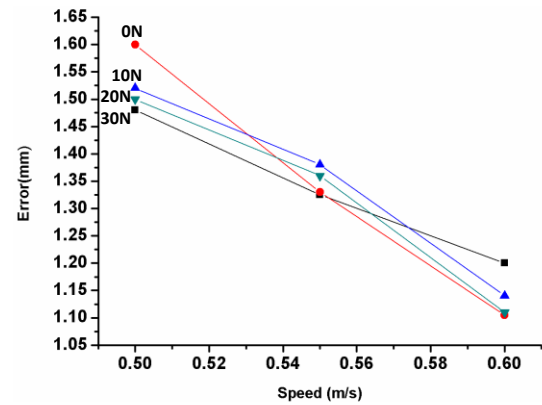
(b) Error of demagnetization position at different speeds and loads

Fig.13. Error analysis.

mover speed is relatively stable, although the estimated speed is not a smooth curve just like the speed calculated by the grating ruler and it changes jumpily, the speed estimation accuracy is still relatively high and its volatility is small. Therefore, the accuracy and feasibility of simplified flux linkage method in estimating the position of the DLSRM has a good performance.

VI. CONCLUSION

This paper corrects the estimated position by modifying the winding resistance value based on the simplified flux linkage method. This method is used to apply the voltage chopping closed-loop speed regulation on DLSRM. We can see from the experimental results that the simplified flux linkage method combining the position estimation and resistance correction methods has a good accuracy on the sensorless control of DLSRM. The motor can operate stably in the case of variable load and target speed. It has accurate position estimation and can realize speed regulation. But there are still some deficiencies that should be solved in the following: If DLSRM operates in single phase mode, its output electromagnetic force is too small. In addition, the speed estimation reflects the average speed of the previous displacement, so its real-time performance is poor.

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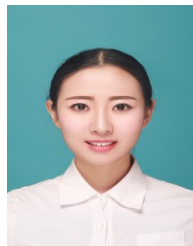
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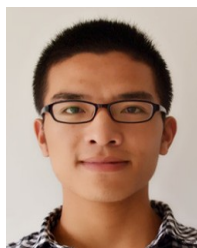
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