A New Simple Sensorless Control Method for Switched Reluctance Motor Drives

Kai Xin†, Qionghua Zhan* and Jianwu Luo*

Abstract - In this paper, a new "impedance sensing" method is described. This method overcomes the shortcomings of the impedance sensing method. According to the new method, sensing voltage pulse is applied to the idle phase in the minimum inductance region and the beginning of the increasing inductance region to detect rotor position. The negative torque produced by the sensing voltage pulse can be neglected in the minimum inductance region and the efficiency of SRM is improved. In the minimum inductance region the back electromotive force (EMF) can be neglected. And in the increasing inductance region the EMF opposes the rise of current in the phase, so the position estimation scheme is reliable. Therefore the new "impedance sensing" method is sufficiently precise even under the high back EMF effect. The adjustment of turn-on angle and turn-off angle is also easy to be realized. The technique is very useful in applications where cost or size is primary concerns, such as electric bicycle drives. Experimental results are presented to verify the proposed method.

Keywords: sensorless control, switched reluctance motor, impedance sensing

1. Introduction

The switched reluctance motor (SRM) has been receiving attention for industrial and domestic applications due to its simplicity, low cost, fault tolerance and high efficiency over a wide speed range. But rotor position sensors are necessary in SRM in order to synchronize the phase excitation to the rotor position. In some systems, these sensors may compromise reliability, and add to size and cost. This has led to attempts to find an alternative way to detect rotor position i.e. indirect rotor position sensing.

Various methods of sensorless position estimation have been investigated for switched reluctance machines [1]. For example, the active phase current detection method using the pulsewidth modulation voltage control [2], the impedance sensing method [3], the monitoring current waveforms method [4], the state observer method [5], [6], the flux-current detection method [7], [8], the mutually induced voltage method [9], the back electromotive force (EMF) method [10], the capacitive sensing method, the combining opposite-connect sensing coils method. The main idea behind all of these methods is to utilize SRM's salient structure. The magnetic status of the SRM is a function of its rotor position. Therefore, one can acquire the position information that is stored in the magnetic characteristic.

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In some applications, such as electric bicycle, reliability, size and cost are primary design criteria. A simple sensorless control method with no extra hardware and high performance digital signal processor required is attractive. Most of the proposed sensorless methods require additional hardware or large lookup tables to store magnetic characteristics. This paper describes a new sensorless control method for the SRM. The presented sensorless control scheme requires neither extra hardware nor huge memory space for implementation. And it can be implemented in a low-cost microcomputer.

2. Basic Principles of The Sensorless Scheme

2.1 Principles of The Impedance Sensing Method

The principles of the position estimation scheme, which we refer to as impedance sensing, have been investigated and developed by Stephen R. MacMinn et al. (1992)[11]. The basic voltage equation of each stator phase voltage is given by the equation

$$\begin{aligned} v &= iR + \frac{d(Li)}{dt} \\ &= iR + L\frac{di}{dt} + i\frac{\partial L}{\partial i}\frac{di}{dt} + i\omega\frac{\partial L}{\partial \theta} \end{aligned} \tag{1}$$

where L= phase inductance, R=phase resistance, i=phase current, $\omega = \frac{d\theta}{dt}$=speed, and θ=rotor position.

One can apply voltage pulse to the idle phase winding as Fig. 1 and measure the phase response current to detect the phase inductance. If the voltage pulse is short enough, the phase current remains small, the back EMF and the saturation effect can be neglected, and (1) can be approximated by

$$v \sim L\frac{di}{dt} \tag{2}$$

Thus, the change in phase current resulting from the sense pulse is in inversely proportional to the instantaneous value of the phase inductance. It can be expressed as:

$$L = v\frac{\Delta t}{\Delta i} \tag{3}$$

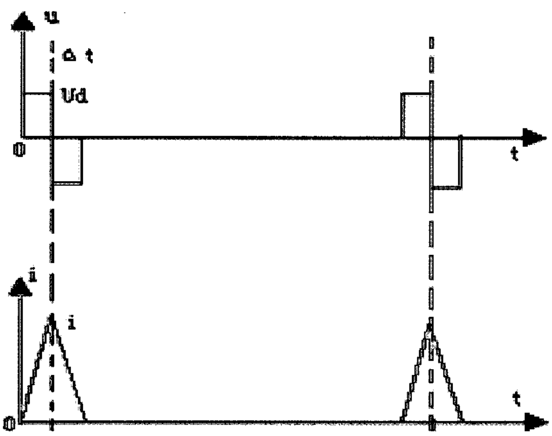


Fig. 1 Pulse voltage and response current

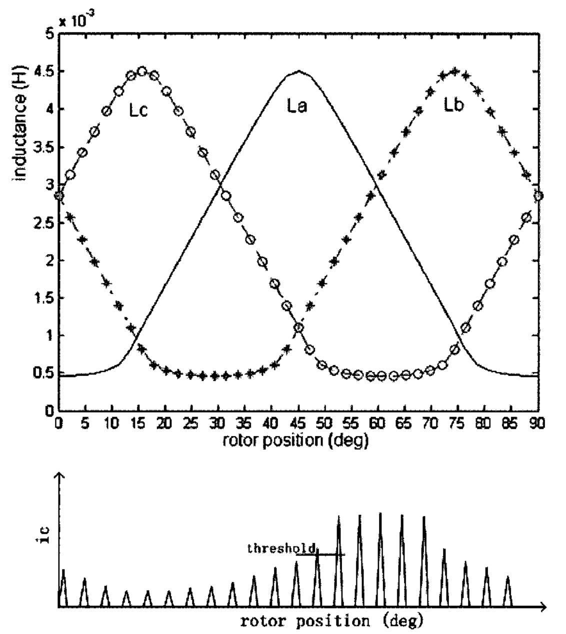


Fig. 2 6/4 SRM inductance profiles and sensing current for phase C

The impedance sensing scheme is shown as Fig. 2. Because only discrete rotor positions need to be detected for successful commutation, rotor positions sensing is accomplished by comparing Δi to a threshold value as shown in Fig 2. In this paper, each phase is assumed to be active for 30° (120° elec.), and only one phase is excited at one time. For example, while phase A is the active phase the last phase C is injected with pulse voltage, the response current i_c is compared with the threshold current. While i_c is greater than the threshold, phase A is turned off, and phase B is turned on. And commutation can be advanced or retarded by reducing or increasing the threshold. In this way, when one phase is active, last phase is sensed to generate the signal for commutation. The rotor speed is estimated by the interval of the commutation signal.

The position estimation method is easy to be realized, and needs no extra hardware, but it still has some disadvantages:

- When one phase is active, last phase is injected with pulse voltage to generate the signal for commutation. But the sensed phase is in the decreasing inductance region, so undesirable negative torque is produced.
- At very high speed operation, the number of the pulse voltage is comparatively not enough in one electrical cycle. The error in the position sensing can not be accepted in this situation. The frequency of the voltage pulse is limited by the switching frequency capability of the power electronic device. And when the frequency is very high, the response current will be too small to be detected.
- The turn-on angle is usually around the unaligned position at low speed. At high speed, the turn-on angle is adjusted in advance of the unaligned position in order to leave enough time for the phase current to build up as high value as possible. It is the angle position control (APC) principle. The APC is realized by reducing or increasing the threshold value in the sensorless control. But at commutation position, the inductance of the last phase is a rather large value, thus the differential of the two consecutive response current is very small. Then the error in the phase current measurement affects the accuracy of the proposed position estimation algorithm significantly.
- The back-EMF can not be neglected at high speed. The error in the position sensing limits accuracy of the communication angle.

In order to improve the performance of the sensorless control method, a new impedance sensing scheme is given here.

2.2 The new impedance sensing scheme

There are two main differentiae between the new impedance sensing scheme and the original one. 1) The original method is to sense the last phase to generate the commutation signal. According to the new method, the next phase is sensed. 2) According to original method, the sensing voltage pulse is applied to the last phase in the decreasing inductance region, rotor position sensing is accomplished by comparing Δi to a threshold value. As the new impedance sensing scheme, sensing voltage pulse is mainly applied to the next phase in the minimum inductance region and the beginning of the increasing inductance region to detect rotor position. When the phase inductance begins to increase as the rotor moves from the unaligned position to the aligned position, the response current will decrease rapidly. The change of the response current is used for rotor position detecting. As in Fig. 3, Phase A is the active phase, the next phase B is injected with pulse voltage. While the response current begins to decrease rapidly, phase A is turned off, and phase B is turned on.

At high speed, APC is used to increase the power-output of SRM. Turn-on angle is advanced, so the commutation arithmetic is changed. In the minimum inductance region of the next phase, the response current maintains a certain maximum value as Fig. 3. On the contrary, if the response current is close to the maximum value, the rotor position is in the minimum inductance region of the sense phase. And it is used to generate the commutation signal. For example, if the response current of one phase is produced per 1° at

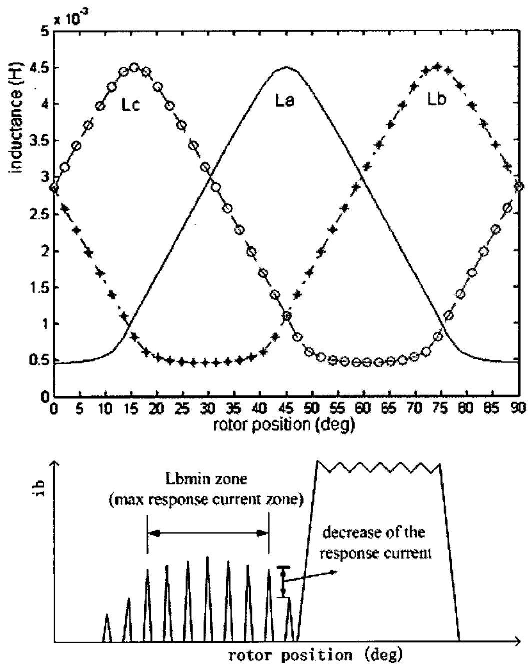


Fig. 3 The new impedance sensing scheme

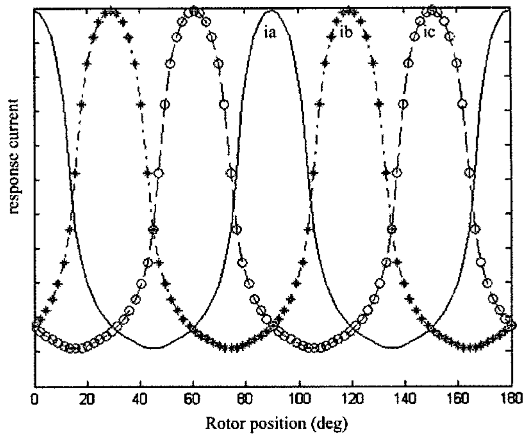


Fig. 4 Envelope of 3 phase response current

current rotor speed, the minimum inductance region is from -4° to 4°, the desired commutation position is -2°, the next phase is turned on when the third maximum response current occurs. And if desired commutation position is 0°, next phase is turned on when the fifth maximum response current occurs.

The most important advantages of the method are the following:

- The method has the merit of simple, less of calculation load and is easy to be realized.
- The negative torque produced by the sensing voltage pulse can be neglected in the minimum inductance region and the efficiency of SRM is improved.
- In the minimum inductance region the back EMF can be neglected. And in the increasing inductance region the EMF opposes the rise of current in the phase, so the position estimation scheme is reliable.
- The adjustment of turn-on angle and turn-off angle is easy to be realized.

The sensorless control method is improved, but it is still not suitable for very high speed applications since the limit of hardware. But it still can be used in many low or middle speed applications, such as electric bicycles. Furthermore, the method need no extra hardware, so it can be conveniently in combination with other sensorless control methods that are not applicable at standstill or not suitable for low speed.

3. Startup

To start up the SRM without using any rotor position sensor, several methods have been introduced.

One of the methods is to align the rotor with one of the stator pole-pairs to provide an initial rotor position.

Another method is to control the SRM in open-loop as a stepper motor. The two methods have some deficiencies, such as inversing and negative torque producing, and can not be used in the situation when the rotor is running. In this paper, two different startup methods are chosen at standstill and running separately.

At standstill, each SRM phase is excited with a voltage pulse and amplitude of the resulting current is used to detect the initial rotor position [12]. As shown in Fig 4, the rotor position region can be divided into 6 regions according to the amplitude of the resulting currents. Zone 1 is ia>ib>ic; zone 2 is ib>ia>ic; zone 3 is ib>ic>ia; zone 4 is ic>ib>ia; zone 5 is ic>ia>ib; zone 6 is ia>ic>ib. But around certain rotor position, such as $\theta = 15^{\circ}$, ia and ib have close amplitude. The slight difference between ia and ib might not be able to distinguish by the current sampling system due to its limited accuracy or resolution. The order of these two currents may be detected incorrectly. To avoid improper initial active phase chosen, ia is considered as equal to ib. It is treated as an especial situation. Table 1 is the logics for choosing the starting phase.

Table 1 Logics For Choosing the Starting Phase

Current order	Rotor position	Chosen phase
ia>ib>ic	$0^{\circ} < \theta < 15^{\circ}$	C and/or A
ib=ia>ic	Around $\theta = 15^{\circ}$	A
ib>ia>ic	$15^{\circ} < \theta < 30^{\circ}$	A
ib>ia=ic	Around $\theta = 30^{\circ}$	A
ib>ic>ia	$30^{\circ} < \theta < 45^{\circ}$	A and/or B
ib=ic>ia	Around $\theta = 45^{\circ}$	B
ic>ib>ia	$45^{\circ} < \theta < 60^{\circ}$	B
ic>ib=ia	Around $\theta = 60^{\circ}$	B
ic>ia>ib	$60^{\circ} < \theta < 75^{\circ}$	B and/or C
ic=ia>ib	Around $\theta = 75^{\circ}$	C
ia>ic>ib	$75^{\circ} < \theta < 90^{\circ}$	C
ia>ib=ic	Around $\theta = 90^{\circ}$	C

When starting up SRM under running status, the presented sensorless scheme is applied. Sensing voltage pulse is applied to a random phase, the decrease of the response current is used for rotor position detecting.

4. Experimental Results

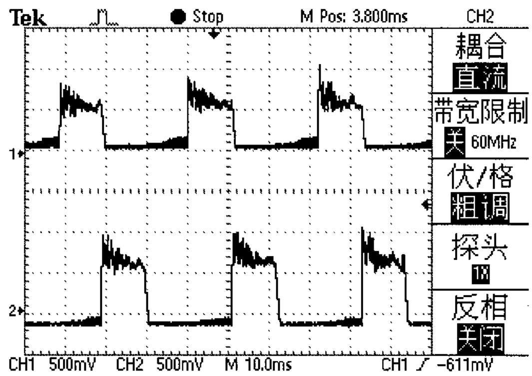
The proposed sensorless control scheme had been implemented on a 150W 6/4 SRM. The characteristics of SRM are shown in Table 2. A permanent magnet dc motor is coupled to the SRM to apply a variable load torque, and a 2000-line encoder is used to evaluate the sensorless control scheme.

Fig.5 presents the testing results from the 6/4 SRM at low and high speed. Fig. 5 (a) shows two phase current at 480r/min; Fig. 5 (b) shows two phase current at 1200r/min. Fig. 6 shows one phase current and its drive signal. When the drive signal is low-level, the switch is on; when the drive signal is high-level, the switch is off.

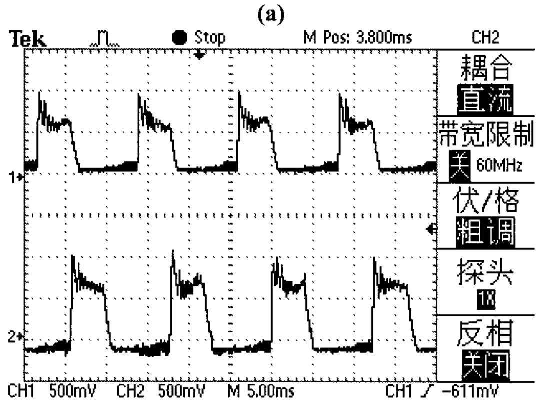
The APC is realized as shown in Fig. 7. Fig. 7 (a) shows one phase current and zone position pulse of the encoder. In Fig. 7 (a) the turn-on angle is not adjusted, the turn-on position is aligned to the zone pulse. In Fig. 7 (b) the turn-on angle is adjusted in advance, the turn-on position is ahead of the zone pulse, hence the current in Fig. 7 (b) is greater than Fig. 7 (a).

Table 2 Motor Ratings

3 phase stator/rotor poles	6/4
Rated power	150W
Rated voltage	36V
Rated speed	3600r/min
Stator pole-arc	33°
Rotor pole-arc	34°
Phase resistance	0.8472Ω
Max. inductance	0.00435H
Min. inductance	0.0003718H



(a)



(b)

Fig. 5 (a) Two phase current waveform at 480 r/min [3.33 A/div 10ms/div] **(b)** Two phase current waveform at 1200 r/min [3.33A/div 5ms/div]

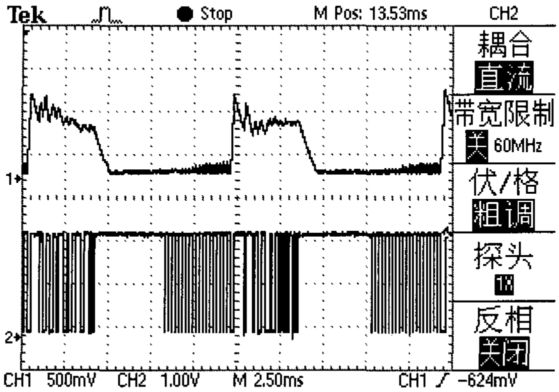
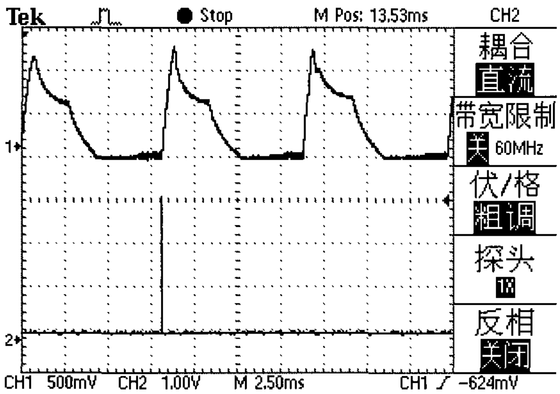
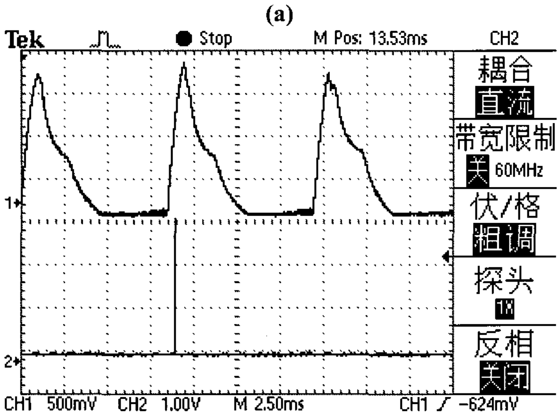


Fig. 6 Phase current waveform and drive signal [3.33A/div 2.5ms/div]



(a)



(b)

Fig. 7 **(a)** Phase current waveform and zone position pulse at *1800* r/min, turn-on angle not advanced [3.33A/div 2.5ms/div] **(b)** Phase current waveform and zone position pulse at 1800 r/min, turn-on angle advanced [3.33A/div 2.5ms/div]

5. Conclusion

A new impedance sensing method is introduced in this paper. The new method is compared with the original one. By injecting sensing voltage pulse to the next phase in the minimum inductance region and the beginning of the increasing inductance region, rotor position is detected. The turn-on angles can be varied freely. The technique is expected to be important in low cost applications. Experiment results are presented to verify the proposed method.

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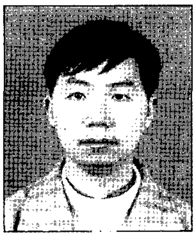

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