Rotor Position Detection of Switched Reluctance Motors Via Transient Voltage Suppressor Circuits

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ABSTRACT: This paper presents a new sensorless rotor position detection for a three-phase single switch SR motor with regeneration capability at standstill mode. The proposed method is based on the dependency of phase current waveform at turn off time to rotor position angle. It is shown that the combination of a motor with single switch per phase converter and a transient voltage suppressor (TVS) circuit define a resonant circuit. It means, the resonance frequency of the circuit depends on the rotor position. In this method, the rotor position is achieved by inspecting of regeneration current results of applied high frequency and low level diagnostic pulses to the motor phases at the beginning step. To obtain the rotor position of switched reluctance motors (SRMs) by meaning of the overlap of rising voltage measurements. During this interval, rotor position is detected by exchanging energy between the phase and source repeatedly in one cycle of a phase current. The resulting current magnitudes are measured and compared to detect the rotor position. The new configuration enables the motor for self-starting without any other mechanism or starting device. The prototype controller was simulated, fabricated, and tested in laboratory and experimental results of the proposed SRM drive system are presented.

Keywords: Rotor Position Detection, Sensorless, Single Switch SRM, Transient Voltage Suppressor.

INTRODUCTION

Many interesting sensorless methods for the switched reluctance motor have been proposed by researchers over the years (Asgar et al. 2009; Kazemi et al. 2010 a,b; Afjei et al. 2008; Afjei et al. 2007). Despite advancements in sensorless control strategy, none of the present schemes has been fully able to replace the mechanical sensor without putting some limitations in the drive. However, the developed methods are application specific, depending on factors like, motor characteristics, converter topology, control strategy etc. Recently, there has been enormous interest in eliminating the mechanical rotor sensors mainly for two reasons: Reduction of cost and Operation in a harsh environment. Furthermore, the requirement for mechanical mounting of the rotor position transducer complicates the drive design, increases the requirement for maintenance, and is a possible source of failure.

The position information is obtained basically from the magnetic characteristics. It is clear from the magnetization curves that the relationship between current, flux-linkage and rotor position is unique but strongly nonlinear which complicates the rotor position estimation. The measurements can be done in an energized or un-energized phase. The magnetization curves of a switched reluctance motor are shown in Figure). It can be observed that the curve at the unaligned position $\theta_u$ is a direct line. In return, the curve for the aligned position $\theta_a$ shows a deflection where the magnetic saturation effect starts.
From the phase voltage (1), it can be observed that the incremental inductance $l$ appears as a function of current and position, and therefore position estimation may be obtained from it. However, it is not an easy task due to the saturation effect (Miller, 1988).

$$V(i, \theta) = R \times i + \frac{d\psi(i, \theta)}{dt}$$  \hspace{1cm} (1)

Where $V$ is the terminal voltage, $i$ is the phase current, $R$ is the resistance per phase and $\psi$ is the flux linkage per phase given by:

$$\psi = l(i, \theta) \times i$$  \hspace{1cm} (2)

Where $l$ is the phase inductance, dependent on the rotor position $\theta$ and phase current $i$. Thus, the phase voltage equation is:

$$= R \times i + \left[ \frac{\partial \psi(i, \theta)}{\partial i} \right]_{\theta=\text{const}} \times \frac{di}{dt} + \left[ \frac{\partial \psi(i, \theta)}{\partial \theta} \right]_{i=\text{const}} \times \frac{d\theta}{dt}$$  \hspace{1cm} (3)

$$= R \times i + l(i, \theta) \times \frac{di}{dt} + e$$  \hspace{1cm} (4)

The first term of (1) corresponds to the voltage due to the phase resistance $R$. The second term is the contribution of the inductive voltage and the third term corresponds to the back-EMF $e$. The second and third terms vary strongly as a function of current level and position (Krishnan, 2001). Accurate measurements of the inductive voltage drop and the back-EMF are difficult when the motor is running. Thus, the both changes significantly as a function of the motor operating point.

The rest of this paper is organized as follows: In section 2 introduces different kind of unenergized phase methods. The review in section 3 presents the circuits for protection and to improve performance which are placed across semiconductor devices. Section 4 includes the description of proposed method, and the experimental results obtained from the new method in rotor position detection of the switched reluctance motor as the statement showed. Section 5 collects some concluding notes and results.

**UNENERGIZED PHASE METHODS**

Different kinds of test signals are introduced or measured during the time when a phase is normally unenergized (i.e. the phases that are not generating torque), normally during the negative slope of the phase inductance when the machine is motoring mode. The test signal needs to be of low amplitude for the following justifications:

- To reduce negative torque generation.
- To avoid saturation results.
- To minimize back-EMF effects.
- To restrict the power rating of additional injection circuitry where this is necessary.

In fact, the fundamental of these methods is to detect the phase inductance or flux variation from the injected signal (Fahimi et al., 2004). The methods that are a member of group are as the followings:

**Active Probing**

This method determining rotor position sensing in a switched reluctance motor (SRM) indirectly. Active
probing techniques are based on instantaneous flux and phase current measurements. The measured current rise time is compared to a threshold current rise time to detecting the communication angle for the succeeding phase. The rotor angle positions for each phase is normalized with consider to a desired reference and then utilized to generate rotor angle estimation for a SRM.

Modulated Signal Injection

In this way, a small high frequency carrier signal from a separate circuit is applied to an unexcited phase and induced phase current is measured in the form of voltage through a sensing component that is connected in series with the inductance of the de-energized phase. The signal containing the phase inductance information has smaller frequency variation compared to the carrier signal and can be decoded using a de-modulation technique to yield the rotor position. Some of the modulation techniques are AM, FM, and PM (Chan, 1987).

Regenerative Current

In this method, the phase is de-energized in response to such current. The control is in soft chopping and the freewheeling current through the diode is observed. When the rotor is in the position of the inductance is increasing, the freewheeling current decays along a negative slope. However, when the rotor passes the aligned position the inductance starts to decrease. Therefore, the negative slope of the freewheeling current is interrupted and starts to increase along a positive slope. This change from negative to positive slope of the freewheeling current indicates when the rotor passed the aligned position (Stephenson and Jenkinson, 2000).

Mutually Induced Systems

This method inducing voltage is expressed as a function of the mutual flux-linkage $\psi_{ml}$ by (5) which varies significantly with rotor position.

$$v_{ind} = \frac{d\psi_{ml}(i_{active}, \theta)}{dt}$$

$$= \left[ \frac{\partial\psi_{ml}}{\partial i_{active}} \right]_{\theta=const} \times \frac{di_{active}}{dt} + \left[ \frac{\partial\psi_{ml}}{\partial \theta} \right]_{i=const} \times \frac{d\theta}{dt} \tag{5}$$

The method seems to be limited to systems using constant current regulation because the mutual voltage induced depends on the level of the current in the excited phase and therefore the current should be constant over the conduction period of the active phase (this means that current profiling is not allowed). It is important to note that the method may be corrupted by noise in the system, because the ratio between induced voltage and system noise is small. This is the main disadvantage of this method. Furthermore, the speed range is limited up to base speed, where there is enough zero current period to observe the induced voltage. The possible advantage is that the method estimates the rotor position by the direct measurement of an internal signal, which is available without the injection of any diagnostic pulses (Barnes and Pollock, 1995).

Transient Voltage Suppressor Circuits

Transient Voltage Suppressor (TVS) Circuits are devices used to protect vulnerable circuits from electrical overstress such as that caused by electrostatic discharge, inductive load switching and induced lightning. Within the TVS, damaging voltage spikes are limited by clamping or avalanche action of a rugged silicon P-N junction which reduces the amplitude of the transient to a non-destructive level.

As a circuit, the TVS circuit should be invisible until a transient appears. Electrical parameters such as breakdown voltage (VBR), standby (leakage) current (ID), and capacitance should have no effect on normal circuit performance.

TVS circuits have operating voltages available in increments from 5V up to higher for some types. Because of the broad range of voltages and power ratings available (as well as the universal presence of transient voltages), TVS's are used in a remarkably wide variety of circuits and applications.

Such protections TVSs are circuits which are placed across semiconductor devices for protection and to improve performance. This can do many things, such as:

- Reduce or eliminate voltage or current spikes.
- Limit di/dt or dv/dt.
- Transfer power dissipation from the switch to a resistor or a useful load.
- Shape the load line to keep it within the safe operating area (SOA).
- Reduce total losses due to switching.
- Reduce EMI by damping voltage and current ringing.

There are many different kinds of TVS circuits but the two most common ones are the resistor-capacitor (RC)
damping network and the resistor-capacitor-diode (RCD).

**Resistor-Capacitor (RC) Design**

These circuits placed across the switch as shown in Figure). That can be used to reduce the peak voltage at turn-off and to damp the ringing. In most cases a very simple design technique can be used to determine suitable values for the R and C Components.

![Figure 2. RC damping circuit.](image)

To achieve significant damping C must be equal to twice the sum of the output capacitance of the switch (CS) and the estimated mounting capacitance. R is selected so that R=V/I. This means that the initial voltage step due to the current flowing in R is no greater than the clamped output voltage. The power dissipated in R can be estimated from peak energy stored in C:

\[ W = \frac{1}{2} CV^2 \]  
(6)

This is the amount of energy dissipated in R when C is charged and discharged so that the average power dissipation at a given switching frequency (f_s) is:

\[ P_d = CV^2f_s \]  
(7)

The RC circuit is very useful for low and medium power applications but when the power level is more than a few hundred watts the loss in the resistor can be excessive and other types of damping circuits need to be considered. The RC circuit does have a place in high power applications as a secondary damping network to suppress high frequency ringing which does not have a lot of energy associated with it (Stephenson and Jenkinson, 2000; Ehsani and Fahimi, 2002).

**Resistor-Capacitor-Diode (RCD) Design**

The RCD circuit as shown in Figure) has several advantages over the RC circuit:

In addition to peak voltage limiting, the circuit can reduce the total circuit loss, including both switching and circuit losses.

Much better load lines can be achieved, allowing the load line to pass well within the SOA.

For a given value of C, the total losses will be less.

The shunt capacitance across the switch (CS) is a useful part of the Circuit (Harris and Land, 1990).

There is one disadvantage however. Because of the diode across R, the effective value for R, during the charging of C, is essentially zero. This is not the optimum value for a given C and E will be higher than it would be in an optimized RC damping circuit.

![Figure 3. RCD damping circuit.](image)

The diode in an RCD circuit has to be rated for at least the peak voltage which appears on C. In general the average current in the diode is relatively small but the peak currents are substantial. The peak current should be the basis for selecting the diode. The diode reverse recovery time (t_{rr}) can affect the circuit action and fast or ultra-fast diodes with t_{rr} < 100 ns are normally used (Al-Bahadly, 2008; Husain, 1996).

The performance of the diode should be verified in the circuit to be sure the circuit is performing as expected. As the voltage rating of the diode is increased and faster recovery diodes are selected, the forward recovery time (t_{fr}) may become a consideration. The reason being is the initial voltage drop across the diode,
but in the forward direction, it can be much higher than the steady state conduction value for several hundred nsec. This problem is exacerbated by the very high $\frac{dI}{dt}$ of typical circuit current waveforms.

By the time, when the diode is completely turned-on, the circuit current pulse may be long terminates. It may be necessary to try several different device types in the actual circuit to get satisfactory performance (Ehsani and Fahimi, 2002).

**Principle Of Sensing**

The initial mode of operation starts at standstill. In this mode all of A, B and C phases are excited by a pattern of short duration pulses and then the shape of currents are studied respectively. In order to detect the rotor position completely with this technique, the shape of step response can be used as a feedback to determine the rotor position of a switched reluctance motor. The control algorithm of this mode is shown in Figure.

![Control algorithm block diagram.](image)

According to this algorithm, the diagnostic pulses with predefine basic frequency and the same amplitude are applied to motor windings. Then, in resonance condition not only the shape of step responses but also the information of rotor direction comparing with together. During the experiment, the torque produced by the test pulses is not significant. If the values of measurement are invalid (beyond resonance), the basic frequency of diagnostic pulses is adjusted to the certain values. With these results, the rotor position is fully recognized.

The real determining factor to defining the exact pulse frequency is the lowest phase inductance (fully unaligned position). It means the resonance condition is happening to such phase that has the highest priority to excite via controller. Then, in standstill mode, sweeping a range of frequency will continue, until the desired phase starts to generate under-damped waveform with ringing frequency.

**ANALYSIS AND SIMULATION RESULTS**

Consider the RLC series circuit shows in Figure. If a rising edge (positive edge) is applied.

![RLC series circuit.](image)
By considering Kerchief’s voltage law (8), Can be obtained:

\[ V(t) = V_R + V_L + V_C \]  \hspace{1cm} (8)

\[ V(t) = R_i + L \frac{di}{dt} + \frac{1}{C} \int i \times dt \]  \hspace{1cm} (9)

Equation (9) is a complex differential equation. However, where the source is an unchanging voltage, differentiating and dividing by L leads to the second order differential equation:

\[ \frac{R_i}{L} \frac{d^2i}{dt^2} + \frac{1}{LC} \frac{di}{dt} + i = 0 \]  \hspace{1cm} (10)

This can be expressed in a more generally relevant form:

\[ \frac{d^2i}{dt^2} + 2\alpha \frac{di}{dt} + \omega_0^2i = 0 \]  \hspace{1cm} (11)

Where \( \alpha \) is called the neper frequency (neper being a unit of attenuation), it is a measure of how fast the transient response of the circuit will die away after the stimulus has been removed. \( \omega_0 \) is the angular resonance frequency. \( \alpha \) and \( \omega_0 \) are given by (12) and (13) respectively:

\[ \alpha = \frac{R}{2L} \]  \hspace{1cm} (12)

\[ \omega_0 = \sqrt{\frac{LC}{L}} \]  \hspace{1cm} (13)

The ratio of these relations is \( \zeta \). It is a useful parameter, which is called the damping factor. \( \zeta \) is given by (14).

\[ \zeta = \frac{\alpha}{\omega_0} = \frac{R}{\sqrt{LC}} \]  \hspace{1cm} (14)

In a switched reluctance motor, the phase inductance \( L \) varies with rotor position and thereby to show critically-damped, over-damped and under-damped conditions, all of other components are considered constant. These three conditions and data calculated are summarized in Table 1. It is mentioned that, this table are normalized for \( R=1 \), \( C=1 \).

<table>
<thead>
<tr>
<th>L[mH]</th>
<th>R[Ω]</th>
<th>C[µF]</th>
<th>( \alpha )</th>
<th>( \omega_0 )</th>
<th>( \zeta )</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>.5</td>
<td>1</td>
<td>1</td>
<td>1.4</td>
<td>.7</td>
<td>( \alpha &lt; \omega_0 )</td>
<td></td>
</tr>
<tr>
<td>.25</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>( \alpha = \omega_0 )</td>
<td></td>
</tr>
<tr>
<td>.01</td>
<td>1</td>
<td>1</td>
<td>50</td>
<td>10</td>
<td>( \alpha &gt; \omega_0 )</td>
<td></td>
</tr>
</tbody>
</table>

Therefore, it is considered, the motor phase inductance changes from \( L_{min} = 10 \) [mH] to \( L_{max} = 500 \) [mH], which \( L_{min} \) is happened in unaligned position and \( L_{max} \) means aligned position. The most relevant simulation in MATLAB environment was the analysis of the critically-damped, over-damped and under-damped responses of a series RLC circuit. The simulation results of the three mentioned status are shown in Figure 6).

By changing the rotor angle relative to the stator pole, phase inductance will change too. During this time, three waveforms shown in Figure 6) possibly occur in resonance condition. Therefore, just need is designed a circuit to detect the difference between these modes. A very important consideration in the following discussions is that the waveform changes are due to changes in the rotor angle.

![Figure 6. Three different responses of a series RLC circuit.](image)

As shown in Figure 6) an implementation scheme of comparing the current waveform with a preset threshold level for commutation is presented. The sample-and-hold circuit is used to capture and hold any one of the
phase current waveforms. The sampling of current waveform is synchronized with phase switching instants.

![Rotor position estimation block diagram scheme.](image)

Thus, the sampling frequency for rotor position detection becomes equal to the PWM frequency. It is mentioned, an Atmel®AVR®ATmega32 microcontroller is used to processes the position information including signal and produces the gate signals for the SRM converter.

### EXPERIMENTAL RESULTS

The selected machine for this experiment is a Three-Phase 6/4, 12V switched reluctance motor. In standstill mode the first phase for initial excitation must be selected, for this purpose a pattern of diagnostic pulses is applied to TVS circuit in each phase (where L is the phase inductance) and by comparing the output current waveform in three phases and considering the direction of rotation proper phase is selected. The mentioned SRM that shown in Figure) has the following characteristic:

![Cross-Section of a Three-Phase 6/4 SRM.](image)

<table>
<thead>
<tr>
<th>Table 2. Motor specifications.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator core outer diameter</td>
</tr>
<tr>
<td>Stator core inner diameter</td>
</tr>
<tr>
<td>Stator arc</td>
</tr>
<tr>
<td>Rotor arc</td>
</tr>
<tr>
<td>Stack length</td>
</tr>
<tr>
<td>Air gap</td>
</tr>
<tr>
<td>Rotor core outer diameter</td>
</tr>
<tr>
<td>Rotor shaft diameter</td>
</tr>
<tr>
<td>Number of turns per pole</td>
</tr>
<tr>
<td>Maximum inductance $L_{\text{max}}$</td>
</tr>
<tr>
<td>Minimum inductance $L_{\text{min}}$</td>
</tr>
</tbody>
</table>

In the static condition the proper phase for initial excitation must be selected. Two factors are considered to select the desired phase. The first is the direction of rotation and second is the amount of aligning between rotor pole and stator pole for the three phases. Considering that the direction of rotation is selected by the user and the other factor must be determined in standstill mode. For this purpose a pattern of test pulses is applied to three phases. The frequency of this voltage is equal to resonance frequency of TVS circuit when the phase inductance (L) has its minimum value and that is when the rotor pole and stator pole are completely in unaligned position. The value of R and C are fixed, but the value of L varies between $L_{\text{min}}$ and $L_{\text{max}}$. The minimum inductance ($L_{\text{min}}$) of the motor phase and the value of capacitor (C) in TVS circuit is equal to 5mH and 10µF, respectively.

Therefore, by considering (13) the frequency of input pattern is calculated. This frequency is equal to 4.5 kHz.

Figure) depicts the phase current and gating signal in unaligned position. As seen in this figure, the result current waveform is showing over-damped condition. Furthermore, another issue that seen in current waveform is 180° phase difference between current pass through TVS circuit and gate signal.
As seen in Figure 9, when rotor and stator are in aligned position, the inductance is increased and $\alpha$ Ratio changes from larger quantity to the smaller one. In this situation, the current waveform is changed from over-damped to the under-damped condition.

To distinguish under-damped condition, it is better that to consider the variation of current waveform from positive value to the negative one. Exist of sinusoidal ringing in current waveform is the best sign to detect the under-damped condition. Therefore, by comparing the comparator output of all phases and considering the direction of rotation the correct phase for initial excitation will be selected.

There are no more factors that should be considered to determination rotor position from this method. However, the effectiveness of this method is largely dependent on the current waveform detection in resonance condition and on the accuracy of the sample timing. This objective can be achieved by sampling the current waveform at the moment and holding the values to compare with the marked values.

In Figure 10, the single stroke is applied to the SRM converter and the response of the TVS circuit is shown that the current waveform is in over-damped condition. It means, the rotor position is in unaligned position.

As shown in Figure 11, instead of the unaligned position. When rotor and stator poles are placed in front of each other, the phase inductance is increased to the maximum value. As a result, the current waveform is in under-damped condition. It means, the rotor position is in aligned position.
The laboratory test system for driving a sensorless controller is presented in Figure). The three-phase SRM is rated at 25W has been utilized. The machine is not optimal as the main focus of the project being undertaken has been on control aspects.

A high precision incremental encoder, mounted on the drive load side, has been used for shaft position sensing/speed detection and served only for comparing and monitoring purposes.

CONCLUSIONS

This paper introduces a new method for direct sensing of the rotor position in single switch reluctance motor drive at standstill mode. The new technique is based on a combination of motor phase inductance varies and a transient voltage suppressor (TVS) circuit that produces a resonant circuit. The motor and converter are developed and tested in the laboratory to verify the functionality and feasibility of this technique. The new topology provides ability to start the motor from beginning without the use of permanent magnet or any other external devices, which reduces the motor cost and facilitates the manufacturing process. The set collected is perfectly capable to identifying the rotor position in static mode as well as, choosing the right phase in order to start the motor driving.

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