

Rotor Position Detection of Switched Reluctance Motors with a New Indirect Technique

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ABSTRACT

The aligned to unaligned phase inductance ratio and the number of stator and rotor poles strongly affect the resolution of indirect rotor position sensing methods for switched reluctance motor (SRM) drives. This paper presents a new sensor-less 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. 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. Obtaining the rotor position of switched reluctance motors (SRMs) will done by means 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 resulted current magnitudes are measured and compared to detect the rotor position. The prototype controller was simulated, fabricated, and tested in laboratory and experimental results of the proposed SRM drive system are presented. The new configuration enables the motor for self-starting without any other mechanism or starting device.

KEYWORDS: Modulation Technique, Rotor Position Detection, Sensor-less, Single Switch SRM.

1. INTRODUCTION

Many interesting sensor-less methods for the switched reluctance motor have been proposed by researchers over the years [1]-[5]. Despite advancements in sensor-less 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 have specified applications, 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's data are 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 1. It can be observed that the curve at the unaligned position is in a direct line. θ_u is a direct line. In return, the curve for the aligned position θ_a shows a deflection where the magnetic saturation effect starts.

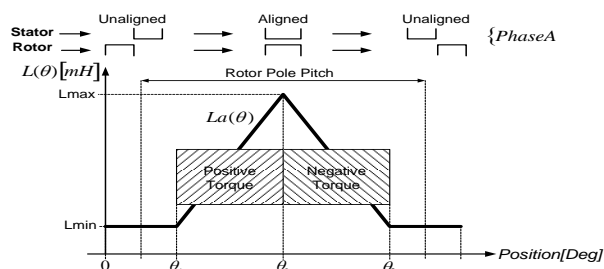


Fig. 1. Linear model inductance profile of active phase

From the phase voltage in (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 [6].

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

Where \mathcal{V} is the terminal voltage, i is the phase current, \mathcal{R} is the resistance per phase and ψ is the flux linkage per phase given by:

$$\psi = \ell(i, \theta) \times i \quad (2)$$

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

$$= \mathcal{R} \times i + \left[\frac{\partial \psi(i, \theta)}{\partial i} \right]_{\theta=cst} \times \frac{di}{dt} + \left[\frac{\partial \psi(i, \theta)}{\partial \theta} \right]_{i=cst} \times \frac{d\theta}{dt} \quad (3)$$

$$= \mathcal{R} \times i + \ell(i, \theta) \times \frac{di}{dt} + e \quad (4)$$

The first term in (1) corresponds to the voltage due to the phase resistance \mathcal{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 [7]. 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 II introduces different kind of un-energized phase methods. The review in section III presents the circuits for protection and to improve performance which are placed across semiconductor devices. Section IV 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 V collects some concluding notes and results.

2. UNENERGIZED PHASE METHODS

Different kinds of test signals are introduced or measured during the time when a phase is normally un-energized (i.e. the phases that are not generating torque), normally during the negative slope of the phase inductance when the machine is in 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 [8]. The participated methods of a group are as the followings:

2.1. Active Probing

This method determining rotor position sensing in switched reluctance motor 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 in order to detect 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.

2.2. Modulated Signal Injection

In this course, 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 [9].

2.3. 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 increased inductance, 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 [10].

2.4. Mutually Induced Systems

This inducing voltage method is expressed as a function of the mutual flux-linkage by equation (5) which varies significantly with rotor position.

$$v_{ind} = \frac{d\psi_{ml}(i_{active}, \theta)}{dt} = \left[\frac{\partial \psi_{ml}}{\partial i_{active}} \right]_{\theta=cst} \times \frac{di_{active}}{dt} + \left[\frac{\partial \psi_{ml}}{\partial \theta} \right]_{i=cst} \times \frac{d\theta}{dt} \quad (5)$$

The method seems to be limited for 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 noise system 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 [11].

3. BIFILAR 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 (V_{BR}), standby (leakage) current (I_D), 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 TVSS' protections 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).

3.1. Resistor-Capacitor (RC) Design

These Circuits placed across the switch as shown in Figure 2. 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.

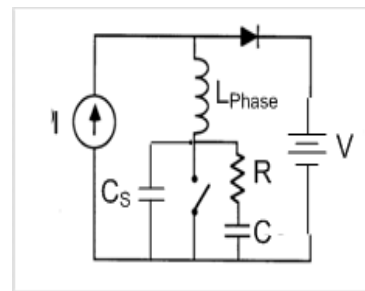


Fig. 2. RC damping circuit

To achieve significant damping C must be equal to twice the sum of the output capacitance of the switch (C_s) and the estimated mounting capacitance. The 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 :

$$W = \frac{1}{2} CV^2 \quad (6)$$

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:

$$P_d = CV^2 f_s \quad (7)$$

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 [12]-[13].

3.2. Resistor-Capacitor-Diode (RCD) Design

The RCD circuit as shown in Figure 3 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 (C_s) is a useful part of the Circuit [14].

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.

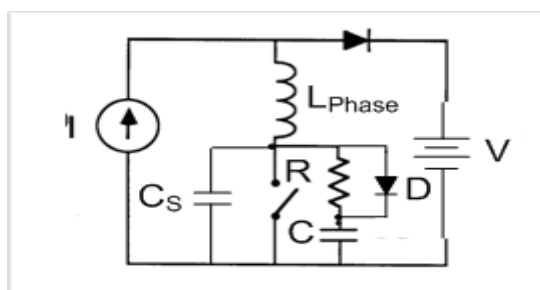


Fig. 3. RCD damping circuit

The diode in the 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 [15].

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 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 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.

4. 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 the following block diagram.

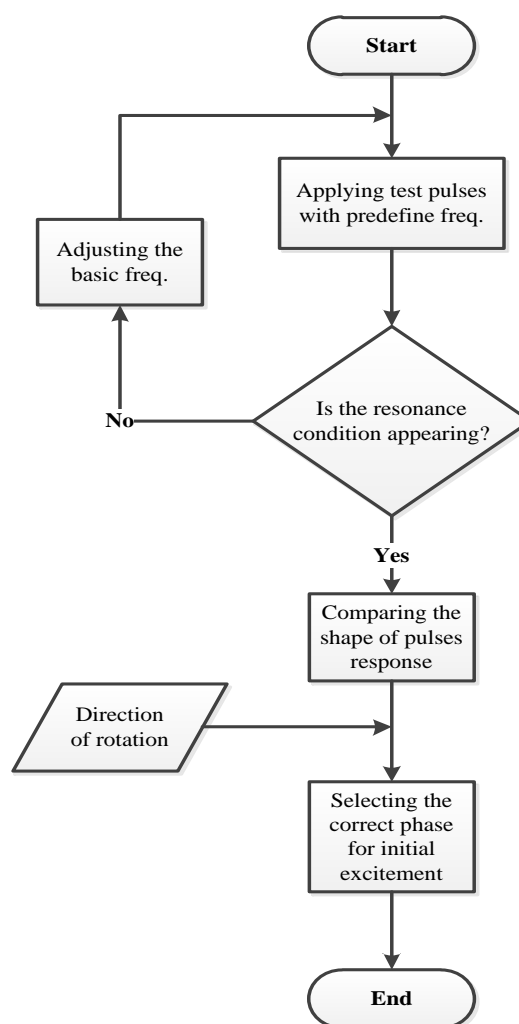


Fig. 4. Control algorithm block diagram

According to this algorithm, the diagnostic pulses with predefine basic frequency and the same amplitude are applied to motor windings. Then, the shape of step not only responses in resonance condition but also the information of rotor direction will be compared. 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 define 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.

5. ANALYSIS AND SIMULATION RESULTS

Consider the RLC series circuit shows in Figure 5. If a rising edge (positive edge) is applied.

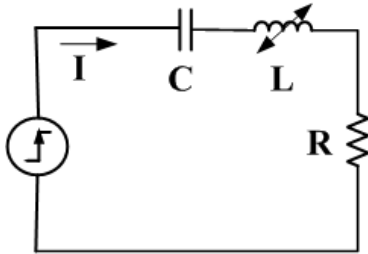


Fig. 5. RLC series circuit

By considering Kerchief's voltage law in (8), Can be obtained:

$$V_{(t)} = V_R + V_L + V_C \quad (8)$$

$$V_{(t)} = Ri + L \frac{di}{dt} + \frac{1}{C} \int i \times dt \quad (9)$$

In (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:

$$\frac{Rdi(t)}{Ldt} + \frac{d^2i(t)}{dt^2} + \frac{i(t)}{LC} = 0 \quad (10)$$

This can be expressed in a more generally relevant form:

$$\frac{d^2i(t)}{dt^2} + 2\alpha \frac{di(t)}{dt} + \omega_0^2 i(t) = 0 \quad (11)$$

Where α 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. ω_0 is the angular resonance frequency. α and ω_0 are given in (12) and (13) respectively:

$$\alpha = \frac{R}{2L} \quad (12)$$

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad (13)$$

The ratio of these relations is ζ . it is a useful parameter, which is called the damping factor. ζ is given in (14).

$$\zeta = \frac{\alpha}{\omega_0} = \frac{R}{2} \sqrt{\frac{C}{L}} \quad (14)$$

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 I. It is mentioned that, this table are normalized for $R=1, C=1$.

Table 1. The conditions and data calculated

L[H]	R[Ω]	C[F]	α	ω_0	ζ	Status
.5	1	1	1	1.4	.7	$\alpha < \omega_0$
.25	1	1	2	2	1	$\alpha = \omega_0$
.01	1	1	50	10	5	$\alpha > \omega_0$

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.

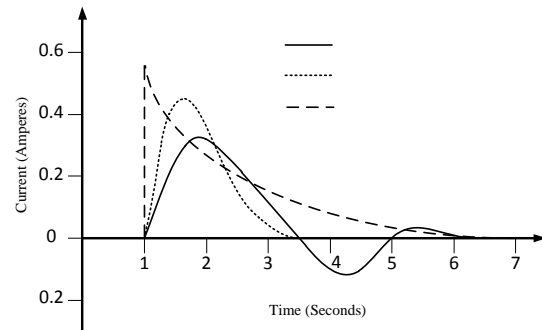


Fig. 6. Three different responses of a series RLC circuit

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.

As shown in Figure 7 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.

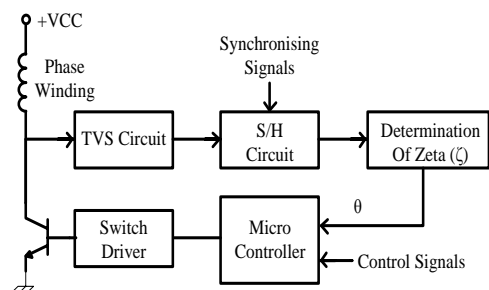


Fig. 7. Rotor position estimation block diagram scheme

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

6. 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 Table 1 has the following characteristic:

Table 2. The Motor specifications

Parameter	Value
Stator core outer diameter	72 [mm]
Stator core inner diameter	62 [mm]
Stator arc	32 [deg.]
Rotor arc	28 [deg.]
Stack length	35 [mm]
Air gap	0.25 [mm]
Rotor core outer diameter	39.5 [mm]
Rotor shaft diameter	10 [mm]
Maximum inductance L_{max}	25 [mH]
Minimum inductance L_{min}	5 [mH]
Number of turns per pole	100

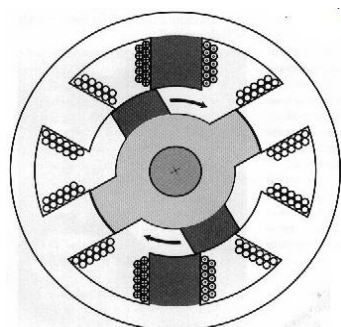


Fig. 8. A cross-Section of a Three-Phase 6/4 SRM

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_{min} and L_{max} . The minimum inductance (L_{min}) of the motor phase and the value of capacitor (C) in TVS circuit is equal to 5mH and 10 μ F respectively. Therefore, by considering in (13) the frequency of input pattern is calculated. This frequency is equal to 4.5 kHz.

Figure 9 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.

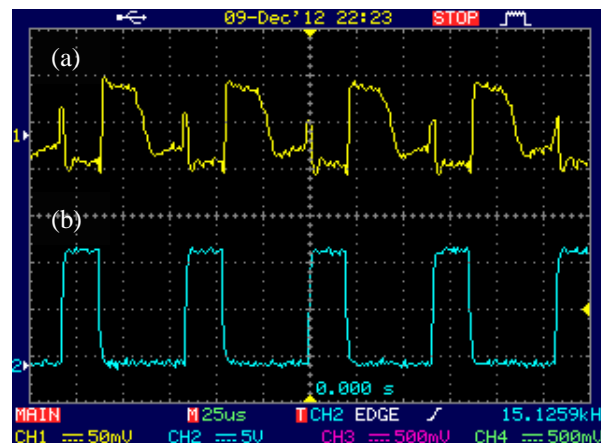


Fig. 9. (1)The current in over-damped condition (2)Gating signal is applied to switch

As seen in Figure 10, when rotor and stator are in aligned position, the inductance is increased and α 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.

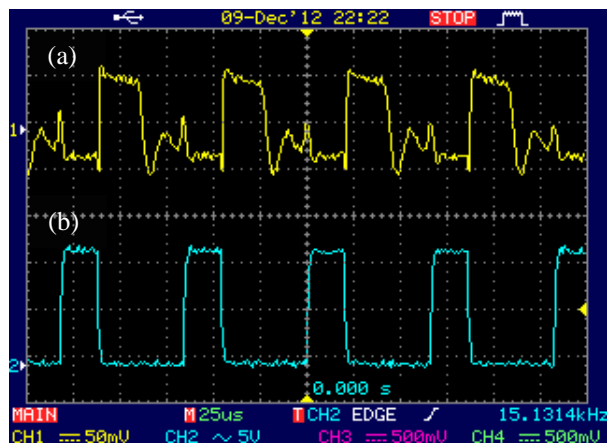


Fig. 10. (a) The current in under-damped condition
(b) Gating signal is applied to switch

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 11, 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.

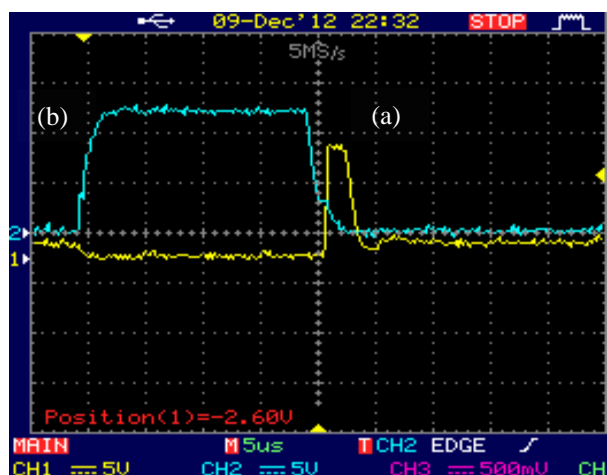


Fig. 11.(a) The current in over-damped condition
(b) Single stroke is applied to switch

As shown in Figure 12, 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.

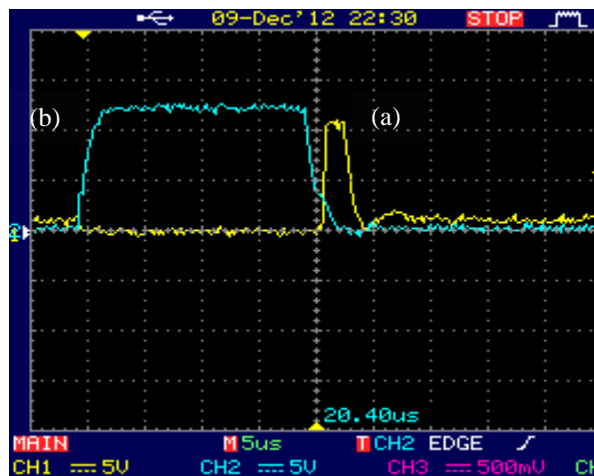


Fig. 12. (a) The current in under-damped condition
(b) Single stroke is applied to switch

The laboratory test system for driving a sensor-less controller is presented in Figure 13. 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.



Fig. 13. The purposed sensor-less controller test system

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.

7. ACKNOWLEDGMENT

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8. CONCLUSIONS

An indirect sensor-less control method for an SRM drive to achieve optimum performance in the presence of parameter variations at standstill mode was presented. 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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