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Rotor Position Sensing Method for Switched Reluctance Motors Using an Indirect Sensor

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ABSTRACT

In this paper, a very low cost and robust sensing method for the rotor position of a TSRM(Toroidal Switched Reluctance Motors) is described. Position information of the rotor is essential for SRM drives. The rotor position sensor such as an opto-interrupter or high performance encoder is generally used for the estimation of rotor position. However, these discrete position sensors not only add complexity and cost to the system but also tend to reduce the reliability of the drive system.

In order to solve these problems, in the proposed method, rotor position detection is achieved using voltage waveforms induced by the time varying flux linkage in the search coils, and then the appropriate phases are excited to drive the SRM.

But the search coil's EMF is generated only when the motor rotates. Therefore the rotor position sensing method using squared Euclidean distance at a standstill is also examined. The simulation and experimental results are presented to verify the performance of the proposed method in this paper.

Keywords: TSRM, rotor position, search coils

1. Introduction

The switched reluctance motor (SRM) has been receiving attention for industry applications due to its low cost in mass production, reduced maintenance requirements, rugged behavior and large torque output over a very wide speed range[1, 2].

It is necessary to get feedback on rotor position information in order to control an SRM.

This paper presents a method using a built-in search coil in TSRM to solve the various problems present in existing position sensors such as the limitation of high speed rotation, the reduction of reliability under high temperature and pressure, the requirement of maintenance on fault and susceptibility to impact.

In the proposed method, rotor position detection is achieved using the voltage waveforms induced by the time varying flux linkage in the search coils, and then the appropriate phases are excited to drive the SRM. But the search coil's EMF is generated only when the motor rotates. Therefore the rotor position sensing method at standstill is also examined.

Both the simulated and experimental results confirm the applicability of the proposed rotor position detection method.

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2. Proposed Position Detection Method

2.1 Configuration of search coil

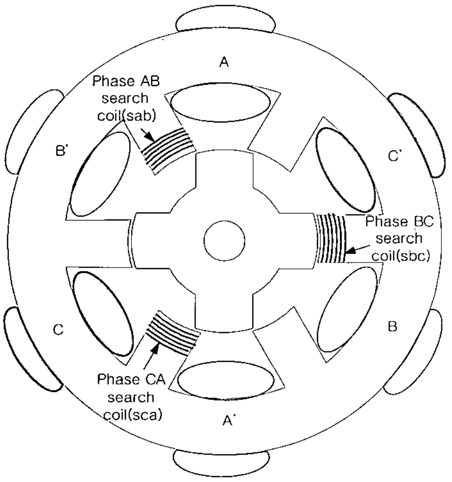


Fig. 1 Installation of the search coil

As shown in Fig. 1, a search coil of 0.16 mm diameter and 10 turns is placed on alternate poles of the stator. The number of turns was chosen considering the rating of the TSRM and input voltage of the A/D converter.

Since current does not flow in the search coil, it can be thin, but it has to be strong enough to withstand the mechanical vibration of the motor.

Magnetic flux is generated in the pole when two adjacent phases are excited simultaneously in TSRM[3].

2.2 Estimating initial rotor position

In TSRM and CSRM, the initial rotor position at stand still should be known to start the motor. In the conventional sensorless drive method, the forced alignment method has to be used to start the motor. This method has serious limitations especially in the cases of unidirectional drives[4-6].

In this paper the initial rotor position sensing method, which consists of two steps, is proposed.

At first, the acquisition of search coil's EMF (V_S) and relative position (θ_R) is needed for the mapping of standard value $V_S - \theta_R$.

To produce search coil's EMF three phases are excited successively with a voltage pulse of about 100μs pulse width.

As the current through the phase windings are very small, the motor still remains at stand still.

The EMF produced in the search coil is a function of the phase currents and the value of mutual inductance, which depends on the amount of overlap between the stator and rotor poles.

The search coil's EMF can be expressed as (1).

$$e = -\left(M_{as}\frac{di_a}{dt} + i_a\omega\frac{dM_{as}}{d\theta} + M_{bs}\frac{di_b}{dt} + i_b\omega\frac{dM_{bs}}{d\theta}\right) \qquad (1)$$

This search coil's EMF contains the information about the rotor position.

Therefore, from the search coil's EMF, the estimation of rotor position becomes possible.

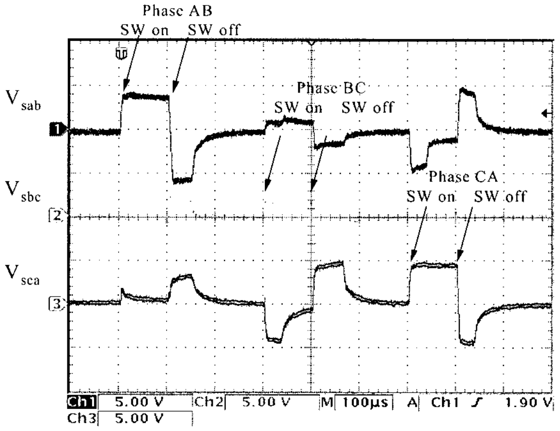


Fig. 2 Waveform of the search coil's EMFs

Fig. 2 shows the EMFs generated in AB, BC, CA phase search coils respectively when TSRM's rotor is in a stationary state and the phase windings are excited by single pulse voltage successively. The amplitude of search coil's EMFs is changed according to the rotor position. Therefore the EMF distribution according to the rotor positions can be acquired by measuring the search coil's EMFs.

Fig. 3 shows the variations of search coil's EMFs with rotor position.

In practice, the EMF distribution as shown in Fig. 3 can not be used directly for the detection of rotor position, because the standard value and measured value taken

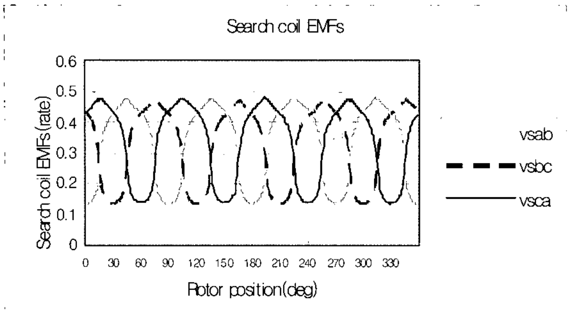


Fig. 3 Search coil's EMFs with rotor positions

exactly at the same rotor position do not give the same value of induced EMFs. They are slightly different for each measurement. This occurs due to the resolution limitations of A/D converters which can not detect minute changes in the rotor position, error of measurement in A/D converters, irregularity in rotor and stator structure, minute vibrations of EMF etc.

This makes it necessary to adopt some technique to select the nearest value to standard rotor position (Fig. 3) corresponding to the measured EMFs. In this paper, squared Euclidean distance method has been used for that purpose.

2.3 Squared Euclidean Distance

The Euclidean distance is the shortest distance between two points in multi dimension space and squared Euclidean distance means the squared value of the Euclidean distance. The distance between x and y is expressed by equation 2.

$$d(x, y) = \| x - y \|^2 = \sum_{i=1}^{k} (x_i - y_i)^2 \qquad (2)$$

A short duration pulse voltage is supplied to each phase of the motor at stand still and the EMFs induced in each phase are measured. The squared Euclidean distance between the measured EMFs and the standard EMFs of Fig. 3 is calculated using equation 3.

$$d_R(k) = \{ Vsab\,* - Vsab(k)\}^2 + \{Vsbc\,* - Vsbc(k)\}^2 + \{Vsca\,* - Vsca(k)\}^2 \qquad (3)$$

$k = 0, 1, 2, \dots, 359$

$d_R(k)$: squared Euclidean distance at position k

$V_{sab}*$: search coil's EMFs of phase ab(measured value)

$V_{sbc}*$: search coil's EMFs of phase bc(measured value)

$V_{sca}*$: search coil's EMFs of phase ca(measured value)

$V_{sab}(k)$: search coil's EMFs of ab phase at position k (reference value)

$V_{sbc}(k)$: search coil's EMFs of bc phase at position k (reference value)

$V_{sca}(k)$: search coil's EMFs of ca phase at position k (reference value)

As described above, when the rotor is positioned at an arbitrary position, short duration pulse voltages are supplied and the search coil's EMF in all of the phases are acquired successively. The squared Euclidean distance between the measured EMFs and the EMFs of the Vs vs. θ_R reference (from 0 deg to 359 deg) is calculated. Here the angle which has the shortest distance value is the current rotor position.

2.4 Using search coil's EMF for estimating rotor position during rotation

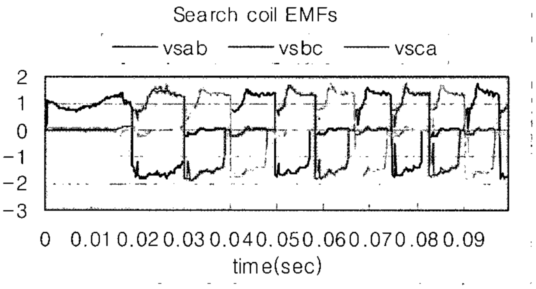


Fig. 4 Simulation waveform of search coils

Fig. 4 shows the search coil's EMFs when the motor is running. The positive parts of the pulses are the period in which the corresponding phases are excited and the search coil's EMFs contain information about the rotor position.

In Fig. 5, T1 is the time interval between the initial point of the torque zone of the search coil's EMF induced by the previously excited phase and induced by the next excited phase.

In the case of a three-phase, 6/4 pole SRM, this T1 interval corresponds to 30 mechanical degrees. If the 30° are divided by T1, the current rotor speed can be calculated.

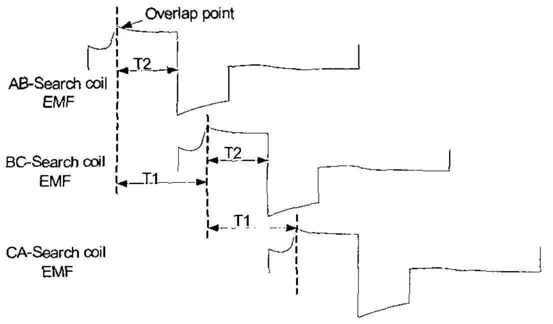


Fig. 5 Control principle using search coils.

T2 is the torque zone and can have the maximum value of 30°. The commutation is done after T2. Because T1 is equivalent to 30° rotor position change, by detecting the initial point of the torque zone and knowing a current speed, the commutation point can be determined.

$$T2 = \alpha T1 \tag{4}$$

Here, α is the ratio of the positive active torque zone to the total positive torque zone and the time duration of T1-T2 is advance angle of the next excited phases.

This driving method which uses search coils can also be applied for backward driving also.

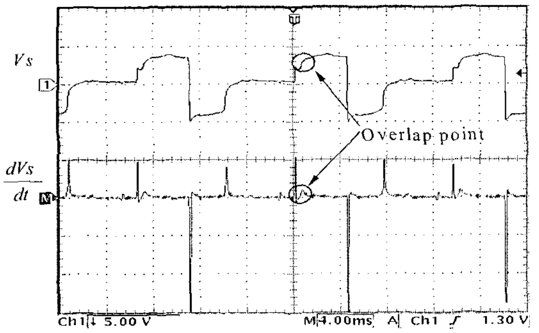


Fig. 6 Search coil's EMF and its differential waveform

Fig. 6 shows the search coil's EMF and its derivative waveform as a method of detecting the initial point of the torque zone.

As can be seen in the derivative waveform, the required point can be detected easily.

The starting point of overlap (the initial point of the torque zone) is the point at which the derivative waveform becomes zero after being positive.

When the search coil's EMF is fed to the controller, moving average method is used to eliminate noise. But this method cannot be used at high-speed because of the time delay it requires.

3. Experimental results

3.1 Estimating initial rotor position

The initial rotor positions of the motor at all angles were estimated using squared Euclidean distance method. As shown in Fig. 7 and Fig. 8, a good agreement between the estimated and true values proves the excellence of the proposed method.

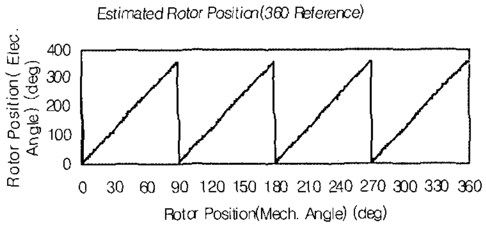


Fig. 7 Estimated rotor position

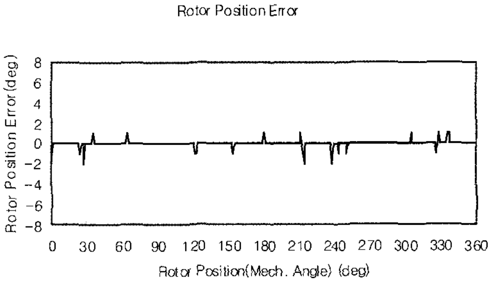


Fig. 8 Rotor position error

3.2 Estimating rotor position during rotation

Fig. 9 shows the search coil's EMFs after the detection of initial rotor position at start up. Short voltage pulses were applied five times before starting the motor in order to insure the correct detection of initial rotor position.

Search coil's EMF waveforms have been reversed due to the inverting amplifier used.

Fig. 9 and Fig. 10 show that magnetizing suitable phases after acquiring current rotor position can achieve smooth starting of the motor.

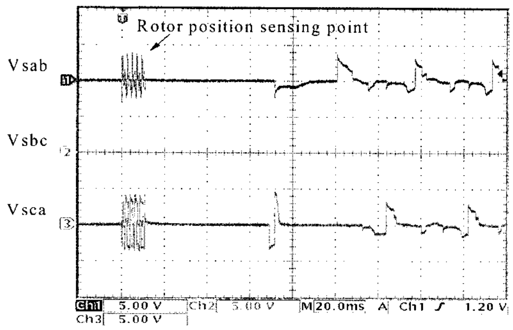


Fig. 9 Initial rotor position sensing

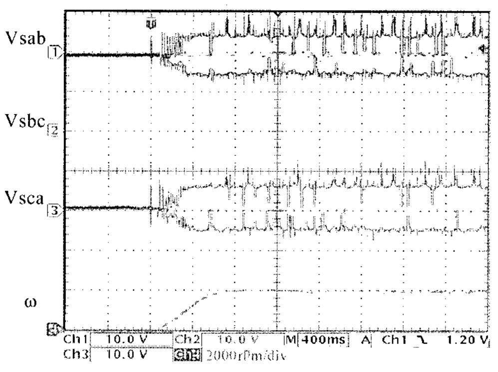
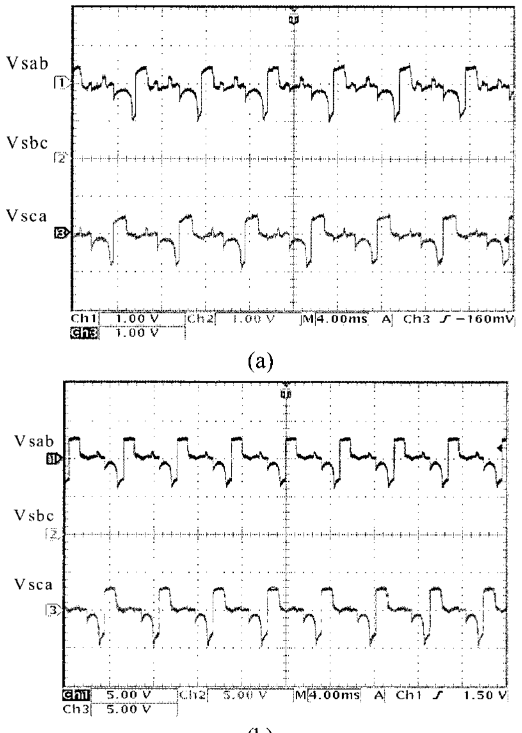


Fig. 10 Startup: search coil's EMFs and speed



(a)

(b)

Fig. 11 Search coil's EMFs

(a) Search coil's EMFs using encoder

(b) Search coil's EMFs using proposed method

Fig. 11(a) shows the search coil's EMFs using encoder and Fig. 11(b) shows the search coil's EMFs using proposed method at running condition. As the both methods give similar waveforms, it is proved that it is possible to drive the motor without using an encoder.

Fig.12 shows drive characteristics in the case of overload. When a heavy load was applied to the motor the speed suddenly dropped from 4000rpm to almost zero but the motor regained speed after removal of the load.

The proposed method is also applicable to backward drive.

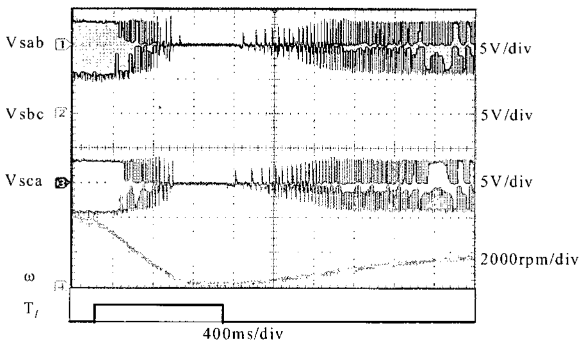


Fig. 12 Performance of the proposed method during load change

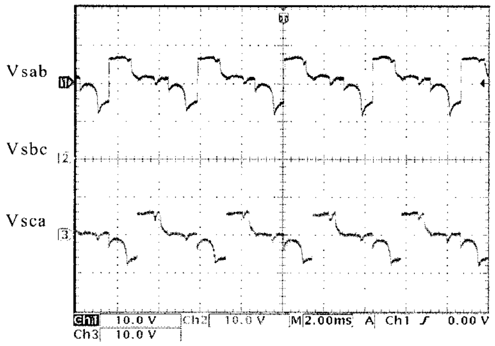


Fig. 13 Search coil's EMFs during reverse drive

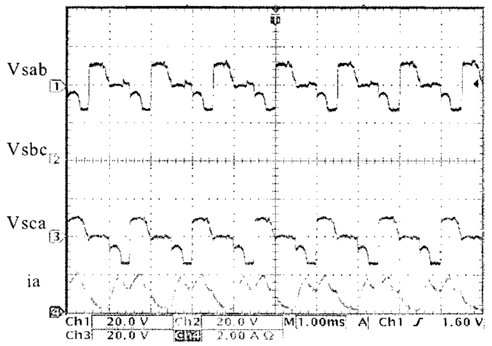


Fig. 14 Performance of the proposed method at high speed (10000rpm)

Search coil waveform during backward drive is shown in figure 13. It shows the reversed sequence in the magnetization of the phases.

Figure 14 is search coil's EMFs waveform and current waveform at 10000 rpm.

The speed limit of high performance encoders is usually 6000 rpm. Therefore, the encoder cannot be used for higher speed applications. But the experimental result in Fig. 14 shows that the proposed method can be used for higher speeds.

This means that the area of application of SRM can be expanded by using search coil as a position sensor.

4. Conclusions

An excellent agreement between the simulated and the experimental results show that the proposed search coil method can be used to detect the initial rotor position at stand still, to start the motor, as well as at running condition to drive the motor. This eliminates the need for separate sensors to detect the initial rotor position. The proposed search coil does not need any external power supply.

This method shows very good results even at higher speeds and this expands the possibility of SRMs' applicability. This system is more compact, highly immune to mechanical impact, vibration and temperature change and does not need frequent maintenance.

The method that has been proposed in this paper seems to contribute greatly in miniaturization and commercialization of low cost SRMs because of the above-mentioned advantages.

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