A New Indirect Rotor Position Sensing with Resonant Method for Switched Reluctance Motor

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A NEW INDIRECT ROTOR POSITION SENSING WITH RESONANT METHOD FOR SWITCHED RELUCTANCE MOTOR

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ABSTRACT

Discrete position sensors are undesirable in our automotive application. We are looking for a sensitive, simple, robust and low cost technique of indirect rotor position sensing method for a doubly salient motor.

This paper describes an original method based on the principle of inductance measurement in the unenergized phase.

A series resonant circuit R L(θ) C is used . L(θ) is the phase inductance varying with the rotor position. The capacitor value is determined by $L_o . C . \omega_{carrier} = 1$ (Lo is the minimum phase inductance).

The resonant circuit is supplied by a high frequency sinusoidal current generator. A synchronous demodulation technique, based on extracting of the maximal amplitude, gives us a voltage signal. This component is a direct measure of the angle linked to the phase inductance.

The advantages of this method are the simplicity, the low cost and the robustness. But the major one is the fact that is amplifies the phenomenon of inductance variation thereby enhancing the accuracy in the measurement of the position angles.

1-INTRODUCTION

The SRM torque is developed by controlling the magneto motive force in accordance with the reluctance variation. The energizing of phase windings must be synchronized with the rotor position. So it requires an angular position sensor.

Physical position sensors are undesirable in our automotive application because of hard environment, assembly problem and cost requirement. We are looking for sensitive, simple, robust and low cost technique of indirect rotor position sensing for a doubly salient motor.

Several authors have described indirect methods of detecting rotor position. These methods and their main disadvantage are :

- Detection of rotor position by monitoring of current waveforms [1] : Difficulties are due to the influence of motor speed, ohmic and electromagnetic losses, switching noise and converter voltage ripples.

- Generating of negative torque by injecting a diagnostic pulse in the unenergized phase [8] and limited resolution with speed increasing.

- Sophisticated method based on a state observer. A fast powerful processor is needed to do real time computation [6]

- Methods based on measuring of the mutually induced voltages [4]. This method requires significantly interphase coupling variation versus the rotor position. The second disadvantage is the magnetic saturation influence.

- Methods based on modulation techniques: the phase, amplitude, or frequency modulations [2],[3]. Usually, a sinusoidal current is applied to the phase coil and we note the phase and amplitude variations of the corresponding voltage due to the varying inductance. In this paper we will show how to increase the accuracy of these methods by a resonant application. This method is based on the comparison of the demodulated voltage amplitude with a reference voltage corresponding to the unaligned position. Most authors identify the electrical parameters of the stator winding with a R-L serial model. The problem lies in the fact that these parameters are very dependant of amplitude and frequency test signal. They seem to be very different from the phase parameters measured in power feeding conditions.

2-PARAMETER IDENTIFICATION METHOD

In this part, we will show the influence of the amplitude and frequency test signal upon the inductive and resistive parameter variation. A first identification is provided by means of alternating current source at 50 Hz, 3A rms. and a second one with our high frequency carrier (30kHz 20 mA rms.). The result of this identification is indicated on figure 1. The two model parameter are computing thanks to a KAPP triangle method.

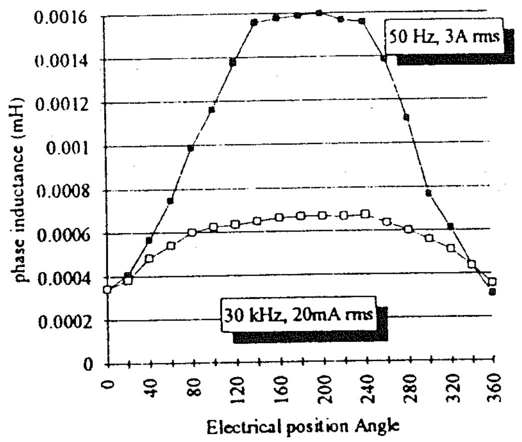

figure 1 : influence of frequency and amplitude level upon the serial inductive parameter.

We see on this figure that the variation of the inductive parameter decreases in high frequency and low level current measurement conditions. The reason of inductance decreasing at high frequency and low level current is probably the diminution of magnetic material permeability. So this problem is less important at aligned position. The resistive parameter of our R-L model is also dependant of these measurement conditions. This is shown in figure 2.

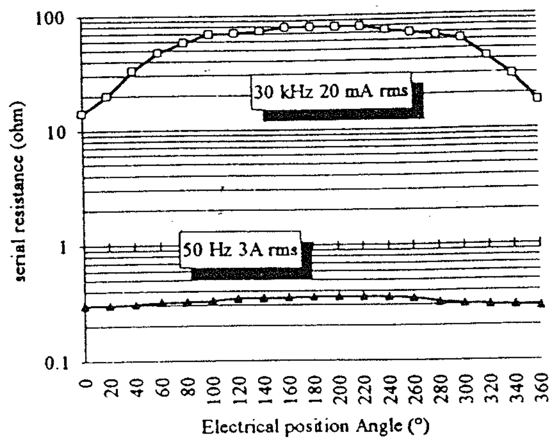

figure 2 : influence of amplitude level and frequency upon the serial resistive parameter.

Here we can see that the resistive parameter will increases with the frequency identification signal. This corresponding variation is shown in figure 3 for the two main positions of rotor:

the unaligned position (rotor angle=0 °)

the aligned position (rotor angle =180°)

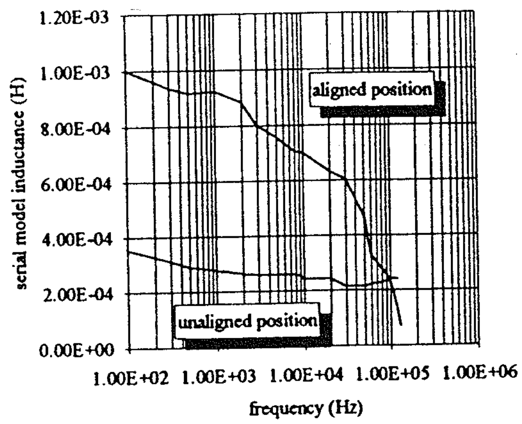

figure 3 : influence of frequency upon the serial inductive parameter :condition 20mA rms.

We can conclude that the choice of the carrier frequency will influence the magnitude of the demodulated voltage. The variation of the inductive parameter between aligned and unaligned positions decreases in high frequency. Besides, the frequency value of the carrier determines the position measurement resolution. So a sufficient frequency value is required in accordance to maximum speed..

If Ω describe the mechanical rotor speed (rpm) and N_r number of the rotor poles (Nr=4 in our application) the electrical frequency is F_e:

$$F_e = \frac{\Omega . N_r}{60} \quad \text{(ex: 200Hz at 3000 rpm)}$$

$$\omega_e = 2.\pi.F_e \text{ electrical pulsation}$$

In case of a q phase machine, the duration of each scanning window is Tscan (s):

$$T_{scan} = \frac{1}{q.F_e} \quad \text{(ex:1.66 ms for 3 phases and 3000 rpm)}$$

Then, each period of the high frequency injected carrier provides one point of position measurement so the global resolution Np (number of point per supply window) is:

$$N_p = F_{carrier}.T_{scan} = \frac{F_{carrier}.60}{q.\Omega.N_r}$$

So the resolution of the measure will linearly increase with the carrier frequency. There is a contradiction between the position resolution and the maximum demodulated voltage variation regardless aligned and unaligned rotor position. In figure 4, we show the relative variation of the inductive parameter between the two main positions of rotor versus frequency modulation.

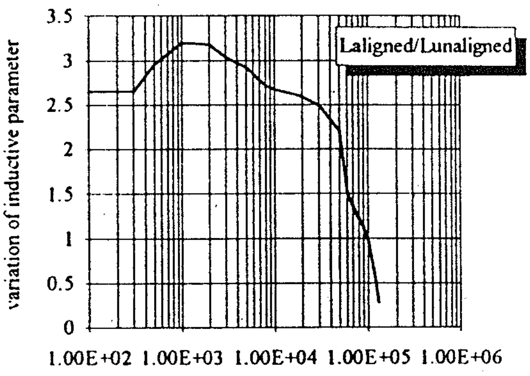

figure 4: relative variation of the inductive parameter between aligned and unaligned position versus carrier frequency (condition: 20 mA rms.)

Then we have to choose a compromize between carrier sensitivity and the dynamic position resolution (especially in high speed). We have chosen a 30 kHz carrier signal. The corresponding inductive parameter variation is about 2,3 (figure 4) and the minimum resolution is 50 points per scanning window at the highest speed (3000 rpm). This gives us a numerical position resolution of 2.4 electrical degrees per point at this highest speed.

The main disadvantage of this method is the low variation of the measuring signal with the rotor position. In order to increase this variation (Laligned/Lunaligned=2,3 at 30 kHz) we propose to virtually increase this variation by the local adjunction of a negative reactive term in the unaligned position. This can be realised by using a RLC resonant circuit. This gives us a measure signal which varies significantly with the rotor position and thereby enhances the accuracy resolution in the measurement of the position angles.

3-INDIRECT RESONANT ROTOR POSITION SENSING PRINCIPLE

A series resonant circuit RL(θ)C is used [5].

L(θ) is the phase inductance value varying with the rotor position.

The resonant capacitor value is determined to obtain : $L_o.C.\omega^2_{carrier} = 1$

Lo: the minimum inductance (unaligned position); $\omega_{carrier} = 2.\pi.F_{carrier}$

By measuring the voltage Ulc (figure 5), we can detect particular position (the unaligned one for our application).The influence of speed effects is reduced because of the serial model resistor containing magnetic losses (iron and copper). The magnetic loss effect is are higher than the ohmic coil and the speed equivalent ones.

The magnetizing equation is described as follow:

$$U_{lc} = (R_{dc} + R_{magnet}).i + i.\omega_e.\frac{dL}{d\theta} + L(\theta).\frac{di}{dt} + \frac{1}{C}.\int i.dt$$

i designate the carrier current, R_{dc} the coil resistor and θ the electrical angle;

$$\text{we put: } R_{eq} = R_{dc} + R_{magnet} + \omega_e.\frac{dL}{d\theta}$$

R_{magnet} represent the sum of electromagnetic losses.

In this equation, the speed influence term is designed by :

$$\omega_e.\frac{dL}{d\theta}$$

w_c design the electrical pulsation. If we adopt a trapezoidal model for the parameter inductance :

$$\frac{dL}{d\theta} \approx \frac{\Delta L}{\Delta\theta} = \frac{L_{aligned} - L_{unaligned}}{\frac{2.\pi}{3}}$$

The $\omega_e.\frac{dL}{d\theta}$ term can be compared with a serial resistor parameter. In the worst case of the application (Ω=3000 rpm) this parameter value is 0.2 Ohm. So we can reasonably missed it in regard to the minimum model resistor value (14 Ohm: figure 2).

The resonant circuit is supplied with high frequency sinusoidal current generator.

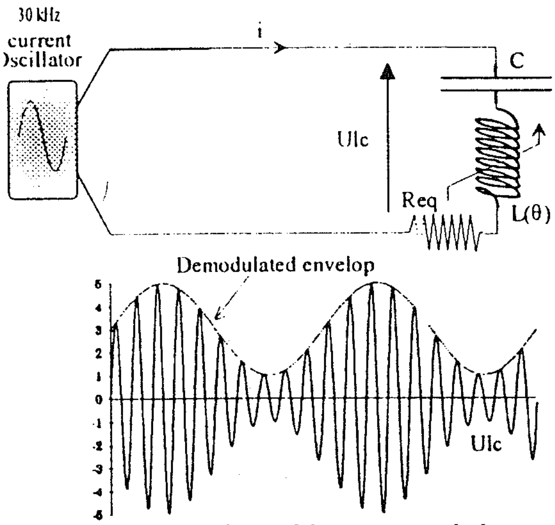

Figure 5: Basic scheme of the measure method

Udemodulated is obtained by a synchronous demodulation technique based on extracting of the Ulc maximal amplitude. This component is a direct measure of the angle linked to phase inductance. The minimum of Udemodulated corresponds to the unaligned position $(L_o.C.\omega^2_{carrier} = 1)$.

With this R-L classic method:

The impedance of serial circuit is determined by:

$$Z(s) = Req(\theta) + L(\theta).s$$

where s is the laplace operator.

At aligned position:

$$|Z| = Z_{max} = \sqrt{R^2_{max} + (L_{max}.\omega_{carrier})^2}$$

At unaligned position:

$$|Z| = Z_0 = \sqrt{R^2_o + (L_o.\omega_{carrier})^2}$$

So the maximum relative variation of the impedance is :

$$\frac{Z_{max}}{Z_o} = \sqrt{\frac{R^2_{max} + (L_{max}.\omega_{carrier})^2}{R^2_o + (L_o.\omega_{carrier})^2}} \approx 2.2 \text{ (cf figure 6)}$$

With R-L-C method:

The impedance of resonant circuit is determined by:

$$Z(s) = \frac{1}{Cs} + L(\theta).s + Req(\theta) = \frac{1 + L(\theta).C.s^2}{Cs} + Req(\theta)$$

At resonant frequency⇔unaligned position:

$(L(\theta)$=Lo and $L_o.C.\omega^2_{carrier} = 1$): Zo=Ro

At aligned position

$(L(\theta)$=Lmax=Lo+ΔL)

$$Z_{max} = \sqrt{R^2_{max} + (\Delta L.\omega_{carrier})^2}$$

So the relative variation of the impedance is:

$$\frac{Z_{max}}{Zo} \approx \sqrt{\frac{R^2_{max} + (\Delta L.\omega_{carrier})^2}{R^2_o}} \approx 7.2 \text{ (cf figure 6)}$$

This RL(θ)C method amplifies the inductance variations and improves the measurement resolution .In figure 6, we present the $\frac{|Z|}{Zo}$ theoretical variation in case of resonant method and (R,L) classic method [2] without resonance.

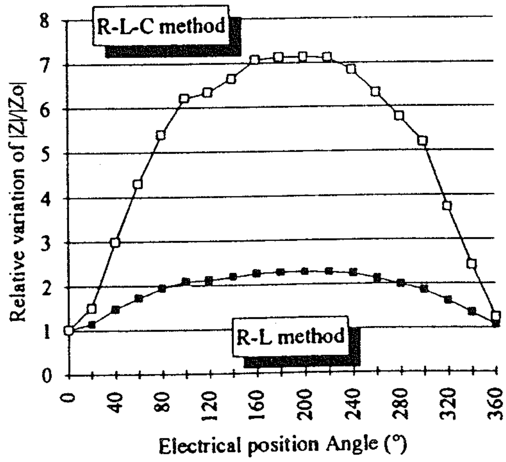

Figure 6: Theoretical |Z|/Zo variation for a R-L and R-L-C method.

4- EXPERIMENTAL RESULTS

We can also compare the two corresponding modulated carrier voltage for each method. This is shown in figure 7 for the R-L method and figure 8 for the RLC one.

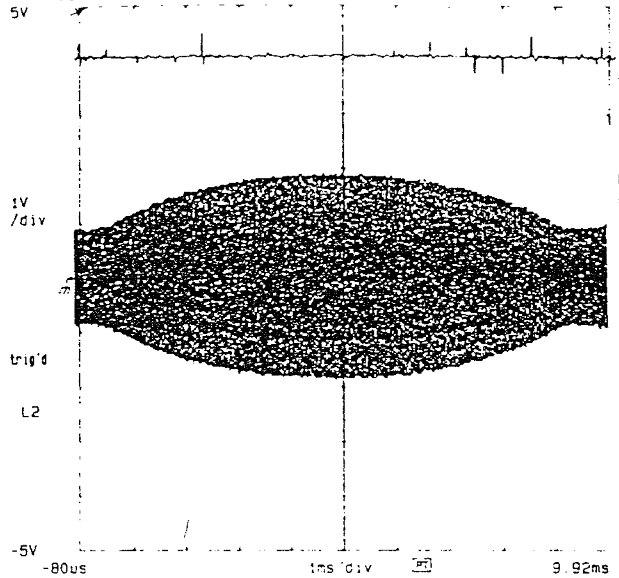

figure 7: example of modulated carrier voltage for a R-L method (carrier=20kHz, 20 mA rms.)

The maximum relative variation is about 2. This is not sensitive enough for a correct determination of the rotor position (especially at the unaligned position).

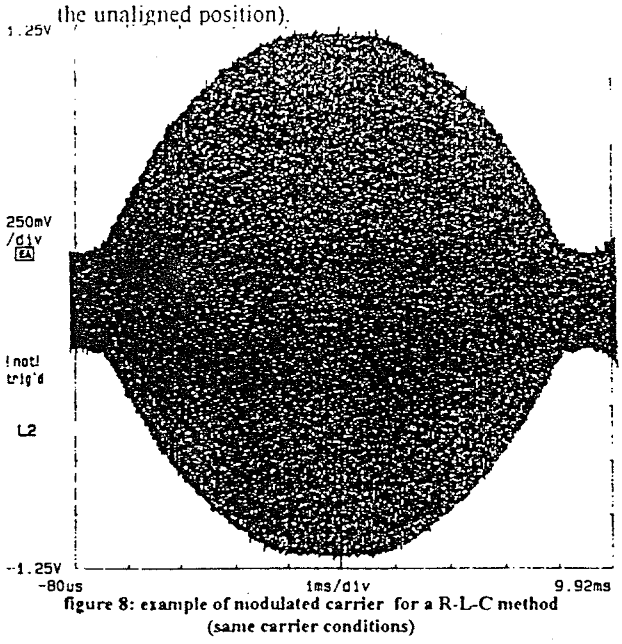

figure 8: example of modulated carrier for a R-L-C method (same carrier conditions)

The maximum relative variation is about 6.5. It becomes sensitive enough especially at the unaligned position. So the accuracy is locally increased at the unaligned position thanks to the resonant circuit.

Figure 9 presents experimental results: Udemo corresponds to the phase number 2 and the drive signal window corresponding to the phase 1.

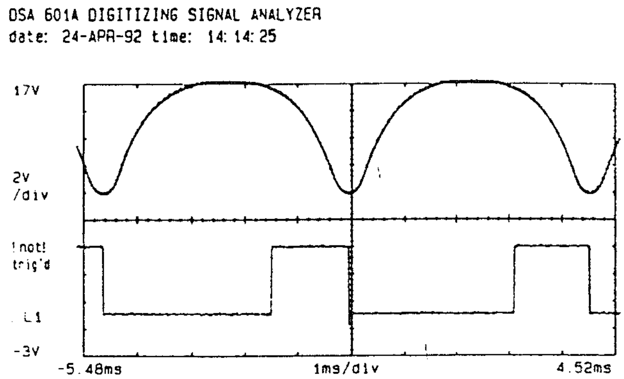

Figure 9 Shape of real demodulated voltage corresponding to the phase number 2 and the drive switching signal of the phase number 1.

This application was tested with a 3 phases SRM (0.1N.m, 3000 rpm) with bifilar windings.

Without feeding of the SRM (rotation is provided by a DC motor), the indirect position signal is reliable as shown in figure 9.

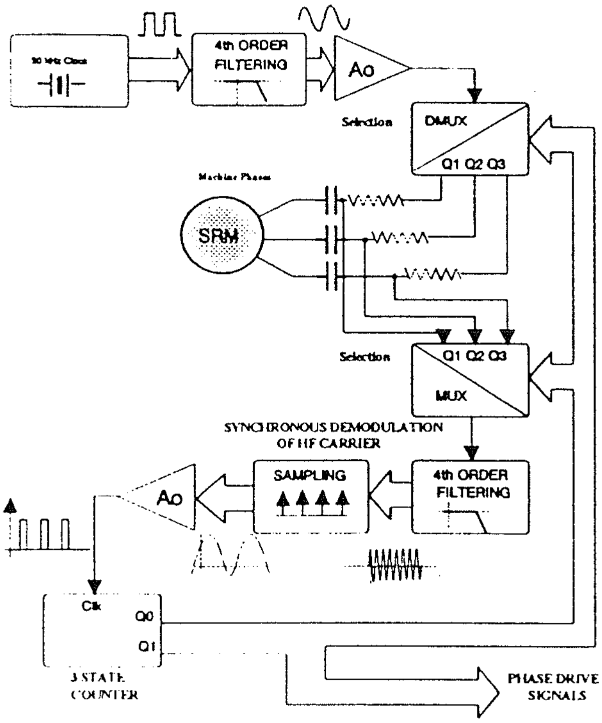

Figure 10: Block diagram of position control

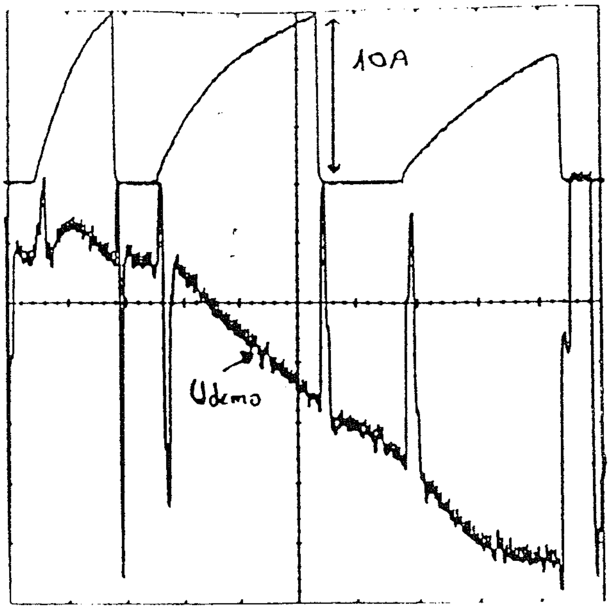

figure 11: demodulated signal before locking of the sampling circuit and shape of the current in the magnetizing coil.

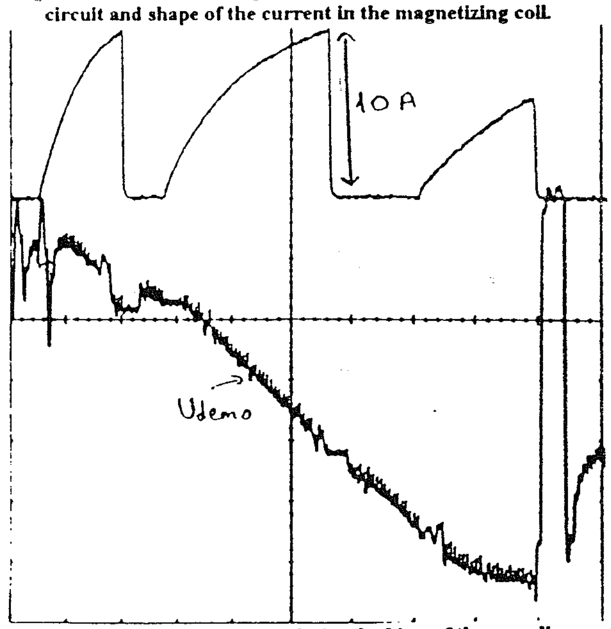

Figure 12: demodulated signal after locking of the sampling circuit and shape of the current in the magnetizing coil

5-ELECTRICAL PERTURBATIONS

When the phases are supplied in pulse width modulation mode or with self switching control [12], converter switching noise appears in the demodulated voltage and the signal becomes polluted. So we have used a method that consists in locking the sampling circuit (synchronous demodulation section figure 10) at each switching instant.

The demodulated signal is also locked during the switch commutation and then there is no more errors transmitted to the position comparator (Ao in figure 10).

Figure 11 and 12 show demodulated signal before and after locking of the sampling with a self switching power converter.

We can see that this locking method allow a good insensitivity to the switching noise.

6-CONCLUSION

The main disadvantage of a carrier injection and demodulation method is the low variation of the measuring signal with the rotor position.

This phenomenon is more important with high frequency and low level excitation carrier signal.[10]. In this paper, we suggested a new method to improve accuracy. This method is base on resonance of phase motor with a serial capacitor . If high speed is required, carrier frequency has to be increased, however, coil impedance becomes capacitive. So it is not ever possible to exploit inductive variation of our model. We can envisage to use equivalent resistor variation (Rmagnet mainly) versus the position measurement (figure 2).

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