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SENSORLESS ROTOR POSITION ANALYSIS USING RESONANT METHOD FOR SWITCHED RELUCTANCE MOTOR

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ABSTRACT

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

This paper describes an experimental modeling of the stator phase with regards to the frequency and amplitude of a sinusoidal carrier and 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 $L_o \cdot C \cdot \omega_{carrier}^2 = 1$ (L_o is the minimum phase inductance).

The resonant circuit is supplied by a high frequency sinusoidal current generator. A synchronous demodulation technique, based on the extraction 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 its simplicity, low cost and robustness. But above all it is the fact that it amplifies the phenomenon of inductance variation, thereby enhancing the accuracy in the measurement of the position angles.

I. INTRODUCTION

The SRM torque is developed by controlling the magnetomotive 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 to determine the rotor position for a doubly salient motor.

Several methods already studied can be divided into two principal families: one that computes the power converter signal such as induced voltage and intensity and the other that use low level high frequency wave signal.

For the first family we can find:

- The detection of the rotor position by monitoring the current waveforms [1] : difficulties are due to the influence of motor speed, Ohmic and electromagnetic losses, switching noise and converter voltage ripples.
- The generation of a negative torque by injecting a diagnostic pulse in the unenergized phase [8] and limited resolution with speed increasing.

- A sophisticated method based on a state observer. A fast powerful processor is needed to do real time computation [6]
- Methods based on measuring the mutually induced voltages [4]. This method requires significant interphase coupling variation versus the rotor position. The second disadvantage is the magnetic saturation influence.

In the second family:

- Methods based on modulation techniques: 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. The main advantage of these methods lies in the nonsensitivity with regard to the speed effect upon the corresponding demodulated signal.

But the relative sensitivity of the method is directly dependant on the amplitude variation of the phase inductance between the two main positions of the machine (aligned position=maximum inductance; unaligned position=minimum inductance). This problem is critical in our application because of the large airgap of the machine. In this paper we will show how to increase the accuracy of these methods by a resonant application.

II. MODELING

In most modulation and demodulation techniques the position information will be dependant either on the modulus, the resistance or the reactance parts of complex stator phase expression (in our case we use an amplitude demodulation by measuring the impedance modulus).

Then, a simple comparison with a reference voltage allows for the determination of a particular position (here the unaligned one). In this part we will show the influence of the amplitude and the frequency test carrier upon the phase model parameters. In order to simplify the study we have chosen a serial R-L model for the stator phase. (in low frequency measurement R corresponds to the Ohmic resistance of the coil and L the phase inductance). At first we will compare the value of these parameters under high frequency and power feeding conditions.

II.A. Inductive parameter

A first identification is provided by means of an alternating current source at 50 Hz, 3A rms and a second one with a high frequency carrier (5kHz and 30kHz 20 mA rms.). The result of this identification is indicated in figure 1. The two model parameters are computed thanks to a KAPP triangle method.

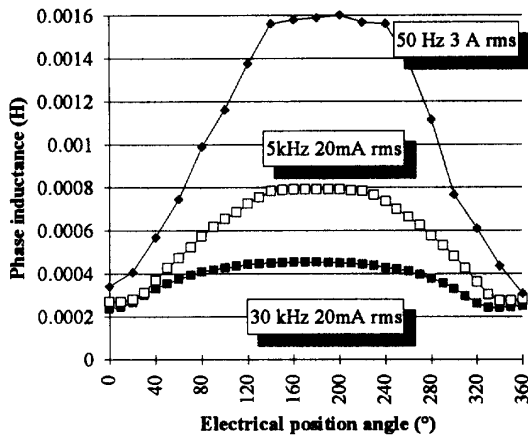


figure 1 : influence of frequency and current level upon the serial inductive parameter L.

We see in figure 1 that the variation of the inductive parameter decreases under high frequency and low level current measurement conditions. The reason for the inductance decrease with a low level current is probably the diminution of magnetic material permeability [10]. So this problem is less important at unaligned position because of the low magnetic flux level (machine fed with a high frequency current generator 20 mA rms.).

So we have studied the frequency influence upon the serial model inductance for the two main rotor positions:

- the unaligned position (rotor angle=0 °)
- the aligned position (rotor angle =180°)

Under high frequency conditions (figure 2) the reactance parameter decreases because of the influence of the winding capacitor. This limits the range of the test signal used for the modulation and induces a limitation upon the angular resolution (the reactance becomes capacitive from 100kHz).

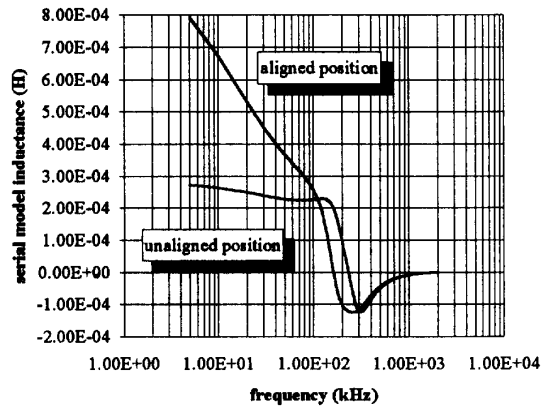


figure 2 : influence of frequency upon the serial inductive parameter :condition 20mA rms.

II.B. Resistive parameter

The resistive parameter of our R-L model is also dependant on these measurement conditions. This is shown in figure 3.

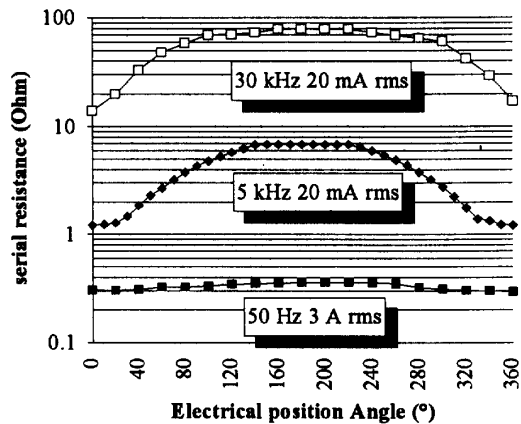


figure 3: influence of frequency and current level upon the serial resistive parameter R.

Here we can see that the resistive parameter will increase with the frequency identification signal either at the aligned

or the unaligned position. We can explain this phenomenon with the magnetic losses and the closeness between wires.

In figure 4 we have also studied the frequency influence upon the serial resistor parameter for the two main rotor positions.

We can notice that the measurement of the resistive parameter gives information about the rotor position up to 100kHz.

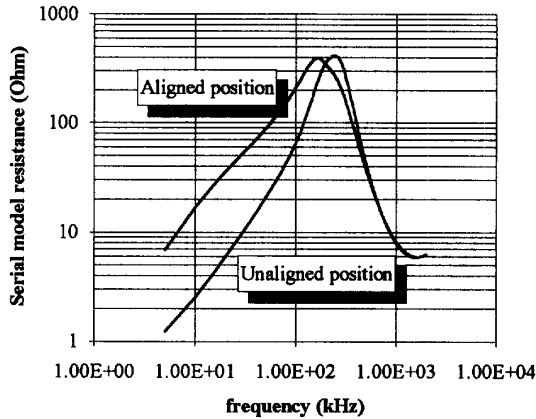


figure 4: Influence of carrier frequency upon serial resistive parameter.

In figure 5 we compare the relative variation of the modulus of the phase impedance, the resistive and the reactive parameter models between aligned and unaligned position versus the carrier frequency choice. We notice that the most sensitive measurement is obtained by using the resistive parameter variation instead of the inductive one (maximum variation of $R_{aligned}/R_{unaligned} \approx 6.8$ for the best carrier condition: 10kHz).

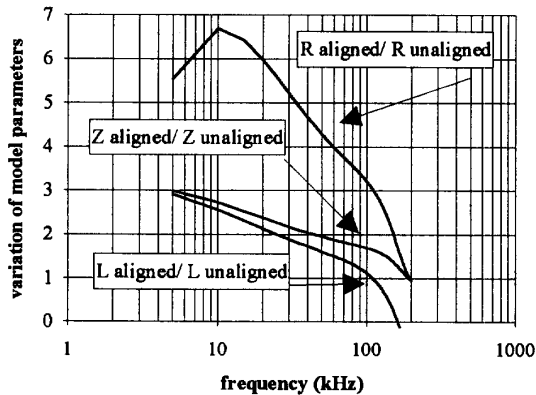


figure 5: relative variation of the three model parameters between aligned and unaligned position versus carrier frequency (condition: 20 mA rms.)

We can conclude that a good choice of the carrier frequency will magnify the amplitude of the demodulated voltage finally obtained.

Besides, the frequency value of the carrier determines the position measurement resolution. So a sufficient frequency value is required in accordance with the maximum speed.

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

$$F_e = \frac{\Omega \cdot N_r}{60} \quad (\text{ex: } 200\text{Hz at } 3000 \text{ rpm}) \quad (1)$$

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

In the case of a q phase machine, the duration of each scanning window is T_{scan} (s):

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

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

$$N_p = F_{carrier} \cdot T_{scan} = \frac{F_{carrier} \cdot 60}{q \cdot \Omega \cdot N_r} \quad (2)$$

So the resolution of the measurement will linearly increase with the carrier frequency. There is a contradiction between the position resolution and the maximum demodulated voltage variation regardless of aligned and unaligned rotor position.

III. INDIRECT RESONANT ROTOR POSITION SENSING PRINCIPLE

The main disadvantage of this method is the low variation of the measuring signal as a function of the rotor position. In order to increase this variation (ex. $L_{aligned}/L_{unaligned}=2,3$ 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 carried out by using a RLC resonant circuit. It gives us a measuring signal which varies significantly with the rotor position and thereby enhances the accuracy resolution in the measurement of the position angles.

A series resonant circuit $RL(\theta)C$ is used [5].

$L(\theta)$ is the phase inductance value varying with the rotor position.

The resonant capacitor value is determined in order to

$$\text{obtain : } L_o \cdot C \cdot \omega_{carrier}^2 = 1 \quad (3)$$

L_o : the minimum inductance (unaligned position);

$$\omega_{\text{carrier}} = 2 \cdot \pi \cdot F_{\text{carrier}}$$

By measuring the voltage U_{lc} (figure 6), we can detect a particular position. In our machine the inductance variation versus the rotor position can be modeled by a trapezoidal shape (see figure 1). So, we decided to adjust the resonant circuit on the unaligned position which appears very clearly. The resonant circuit is supplied with a high frequency sinusoidal current generator.

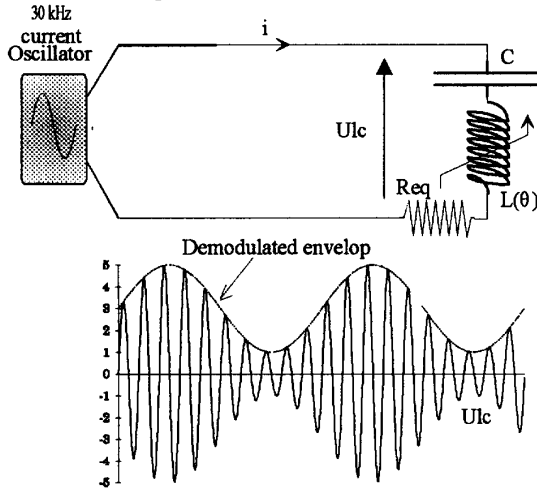


Figure 6: Basic scheme of the measure method

$U_{\text{demodulated}}$ is obtained by a synchronous demodulation technique based on the extraction of the U_{lc} maximal amplitude. This component is a direct measure of the angle linked to the phase modulus parameter. The minimum of $U_{\text{demodulated}}$ corresponds to the unaligned position

$$(L_o \cdot C \cdot \omega_{\text{carrier}}^2 = 1).$$

We will compare two modulation methods with or without use of the resonant circuit.

With this R-L classic method:

The impedance of the serial circuit is determined by:

$$Z(s) = \text{Re} q(\theta) + L(\theta) \cdot s$$

where s is Laplace's operator.

At aligned position:

$$|Z| = Z_{\text{max}} = \sqrt{R_{\text{max}}^2 + (L_{\text{max}} \cdot \omega_{\text{carrier}})^2}$$

At unaligned position:

$$|Z| = Z_o = \sqrt{R_o^2 + (L_o \cdot \omega_{\text{carrier}})^2}$$

So the maximum relative variation of the impedance is :

$$\frac{Z_{\text{max}}}{Z_o} = \sqrt{\frac{R_{\text{max}}^2 + (L_{\text{max}} \cdot \omega_{\text{carrier}})^2}{R_o^2 + (L_o \cdot \omega_{\text{carrier}})^2}} \approx 2.2 \text{ (cf fig 7, 30kHz)} \quad (4)$$

With our R-L-C method:

The impedance of the resonant circuit is determined by:

$$Z(s) = \frac{1}{C s} + L(\theta) \cdot s + \text{Re} q(\theta) = \frac{1 + L(\theta) \cdot C \cdot s^2}{C s} + \text{Re} q(\theta)$$

At resonant frequency \leftrightarrow unaligned position:

$$(L(\theta) = L_o \text{ and } L_o \cdot C \cdot \omega_{\text{carrier}}^2 = 1) : Z_o = R_o$$

At aligned position

$$(L(\theta) = L_{\text{max}} = L_o + \Delta L)$$

$$Z_{\text{max}} = \sqrt{R_{\text{max}}^2 + (\Delta L \cdot \omega_{\text{carrier}})^2}$$

So the relative variation of the impedance is:

$$\frac{Z_{\text{max}}}{Z_o} \approx \sqrt{\frac{R_{\text{max}}^2 + (\Delta L \cdot \omega_{\text{carrier}})^2}{R_o^2}} \approx 6.8 \text{ (cf fig 7, 30kHz)} \quad (5)$$

III.A. Choice of the carrier frequency

We have already noticed that there was a compromise between sensitivity and resolution in the choice of the carrier frequency. On figure 7 we show the influence of the frequency upon the sensitivity of position measurement for the two main positions between the RL and the RLC method.

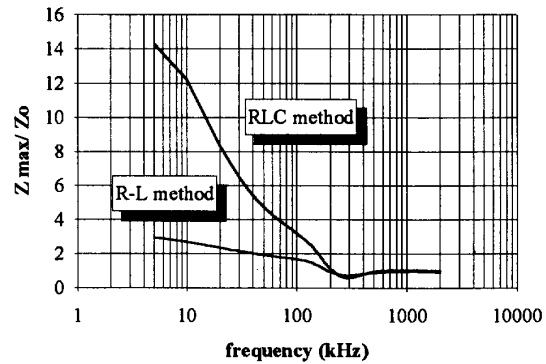


Figure 7: Influence of carrier frequency upon measurement sensitivity.

We have chosen a 30 kHz carrier signal. The corresponding demodulated voltage variation is about 2.3 (figure 7) for the R-L method and 6.8 for the RLC one and the minimum resolution is 50 points per scanning window at the highest speed (3000 rpm) (highest speed is the worst case for the position resolution). This gives us a numerical position resolution of 2.4 electrical degrees per point at this highest speed.

The RL(θ)C method amplifies the equivalent inductance variations and improves the measurement resolution. In figure 8, we present the $\frac{|Z|}{Z_0}$ theoretical variation in the case of the resonant method and (R,L) classic method [2] without resonance.

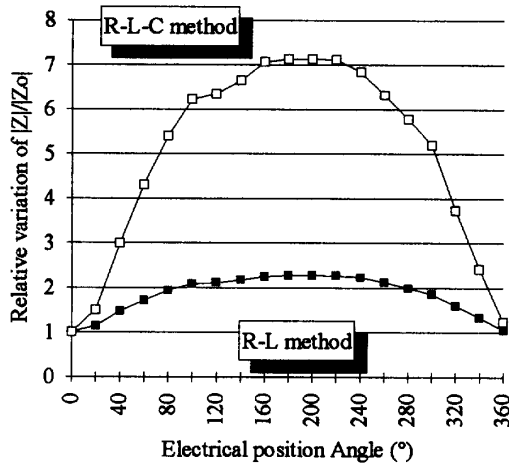


Figure 8: Theoretical $|Z|/Z_0$ variation for a R-L and R-L-C method (30kHz).

However, the damping coefficient is still limited by the unaligned resistive parameter which corresponds to the magnetic losses.

III.B. Speed influence

The influence of speed effects is reduced because of this serial model resistor containing magnetic losses (iron and copper). The magnetic loss effect is higher than the Ohmic coil and the speed equivalent ones.

The magnetizing equation is described as follows:

$$U_{lc} = (R_{dc} + R_{magnet}) \cdot i + i \cdot \omega_e \cdot \frac{dL}{d\theta} + L(\theta) \cdot \frac{di}{dt} + \frac{1}{C} \cdot \int i \cdot dt \quad (6)$$

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

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

R_{magnet} represents the sum of electromagnetic losses.

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

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

ω_e is the electrical pulsation. If we adopt a trapezoidal model for the parameter inductance :

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

The $\omega_e \cdot \frac{dL}{d\theta}$ term can be compared with a serial resistor parameter. In the worst case of the application ($\Omega=3000$ rpm) this parameter value is 0.2 Ohm. So we can reasonably not take it into account with regard to the minimum model resistor value (14 Ω at 30kHz: figure 3).(same results for experimentation.)

III.C. Shifting of the resonant point

When using a SRM in large ranges of speeds it may be useful to advance the ignition angle of the phase before the total unaligned position. We can also shift the minimum of the demodulated voltage by changing the carrier frequency (it modifies the resolution) or the serial capacitor value. We present on figure 9 and figure 10 an example of this technique for a 30kHz and 100kHz carrier.

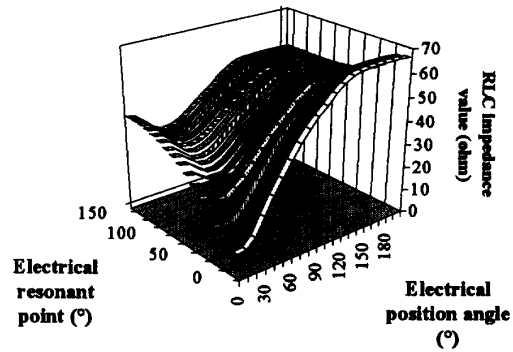


Figure 9: Influence of the resonant point position upon the RLC model impedance (frequency carrier=30kHz).

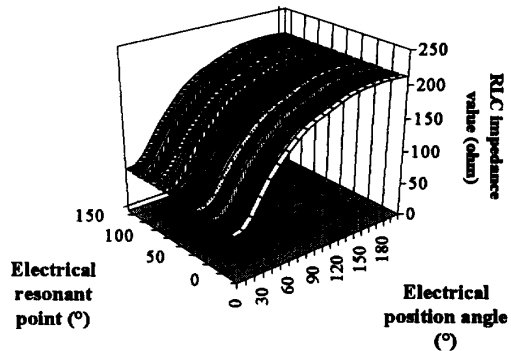


Figure 10: Influence of the resonant point position upon the RLC model impedance (frequency carrier=100 kHz).

We can notice in figure 10 that the shifting method has no influence upon the RLC impedance in this case. This means that the relative variation of the model impedance is no longer dependant on the inductive parameter variation but depends on the resistive parameter only.

IV. EXPERIMENTAL RESULTS

IV.A. Position measurement

This method was tested with a 3 phase SRM (6/4, 0.1N.m, 3000 rpm) with bifilar windings.

Without feeding the SRM (rotation is provided by a DC motor), the indirect position signal is available as shown in figure 11.

To determine the rotor position and so synchronize the power feeding in the stator phase we scan the phase which is about to be energized. This can be done by means of the HF carrier through the analog demultiplexer and multiplexer. As soon as the unaligned position is found (voltage comparator) the 3 state counter provides the phases drive signal toward the power the converter to supply the actual scanned phase. At the same time, the next phase is also scanned.

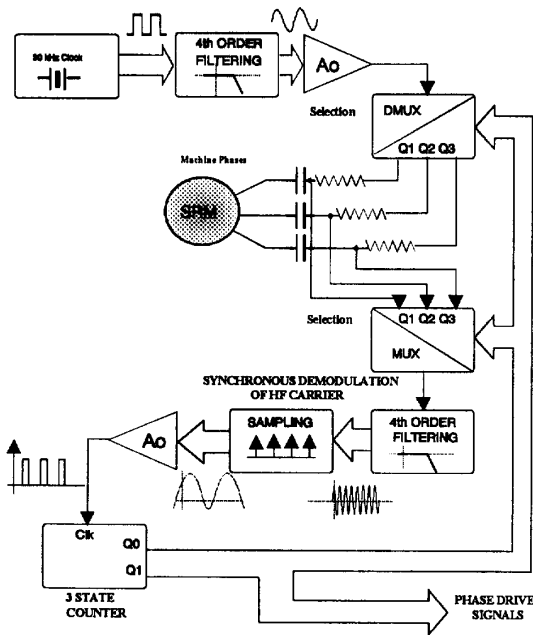


Figure 11: Block diagram of position control

We can also compare the two corresponding modulated carrier voltages for each method. This is shown in figure 12 for the R-L and RLC method (for a 30kHz carrier).

With the RL method the maximum relative variation is about 2.2. This is not sensitive enough for a correct determination of the rotor position because the unaligned position is not defined well enough.

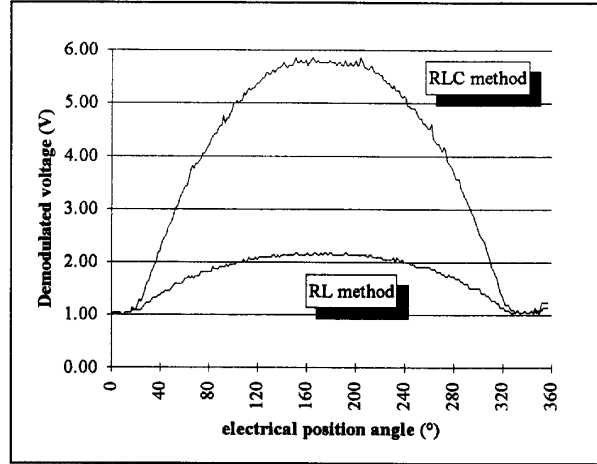


figure 12: example of demodulated carrier voltage for a R-L and a RLC method (carrier=20kHz, 20 mA rms., 3000rpm)

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

IV.B. 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 (in figure 13).

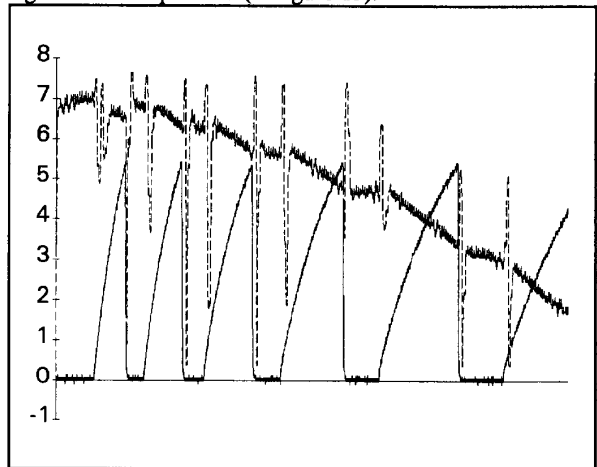


figure 13: demodulated signal before locking of the sampling circuit and shape of the current in the magnetizing coil.

We can synchronize the carrier feeding with the converter commutation or we can lock the sampling circuit (synchronous demodulation section figure 10) at each switching time instant.

These switching times can be determined by observing the demagnetizing diode voltage and a simple logic controls the sampling circuit (figure 14)

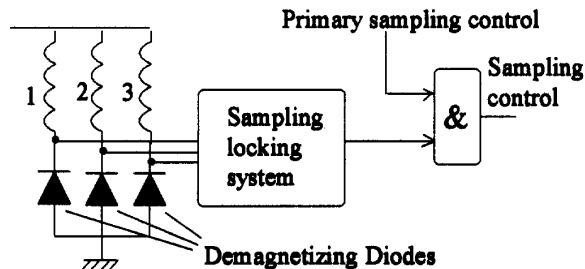


Figure 14 : Description of the logic control for the noise elimination.

This enables us to avoid the use of a classic filtering circuit fed with the demodulated voltage which limits the dynamic response of the position measurement (position error due to phase shift of the filtering unit).

The demodulated signal is also locked during the switch commutation (about $5\mu s$) and then there are no more errors transmitted to the position comparator (Ao in figure 10).

Figure 15 shows the demodulated signal after locking the sampling circuit.

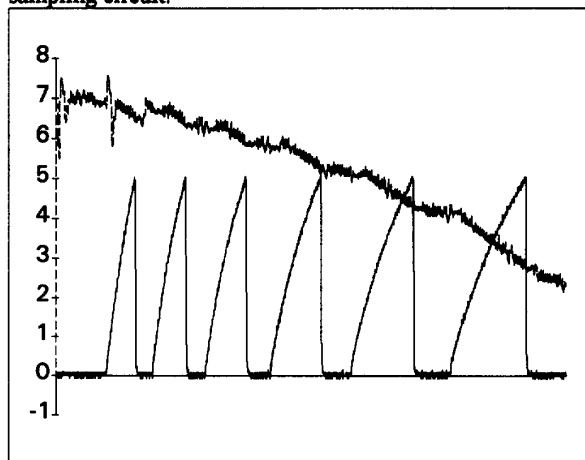


Figure 15: demodulated signal after locking of the sampling circuit and shape of the current in the magnetizing coil.

We can see that with this locking method the switching noise has relatively no influence upon the demodulated signal.

V. FUTURE RESEARCH

One problem of the method lies in the fact that we need a scanning window to determine the position. We will try to apply the process even if all phases are fed at the same time.

At the moment we are studying

- the position measurement by means of the only resistive parameter (very high frequency carrier).
- the influence of temperature upon this last parameter and the induced effect upon the final demodulated voltage.
- the influence of the phase turn number on the resistor and the capacitor values and the suitable carrier frequency.

VI. CONCLUSION

The main disadvantage of the classical method using carrier injection lies in the low variation of the measuring signal with the rotor position especially under high frequency and low magnetic field level.

We have seen in the first part that an experimental identification was necessary to choose the best parameter model in the position measurement.

This allows for the optimal choice of the frequency which gives us a reasonable compromise between sensitivity and resolution. If high speed is required, carrier frequency has to be increased, however, coil impedance becomes capacitive. So it is no longer possible to exploit inductive variations of our model.

Finally, shifting the resonant point gives results as long as the reactive parameter remains a preponderant term in the impedance model.

In that case, we can consider to use equivalent resistor variation (R_{magnet} mainly) versus the rotor (figure 5).

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