PERMANENT MAGNET SYNCHRONOUS MOTOR SENSORLESS DRIVE USING A DSP

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Abstract **— This work presents a permanent magnet synchronous motor drive without a position sensor. The position estimation is implemented by means of a DSP (Digital Signal Processor). The estimation algorithm is based on the information of phase voltages and currents to obtain the back emf's, which are used to estimate, indirectly, the rotor position. At motor starting, an initial position detection algorithm is implemented, and for low speed operation, an auxiliary open loop algorithm is implemented. The objective of this work was the implementation of a low cost system, but with a good performance, for general applications of variable speed drives.**

I. INTRODUCTION

The research on sensorless permanent magnet synchronous motors drives, using estimation, has such level of development, that the position estimation only presents bigger difficulties for low speeds [1, 2]. There are two basic strategies for the position estimation, which are: the use of phase voltages and currents of the motor (fundamental component) and the use of rotor's saliency, through signals injection.

In the method of using motor's phase voltages and currents, the motor is fed by an inverter, with a switched signal, to compose a voltage or current fundamental component, implying in the appearing of speed voltages (back emf's). In this case, the techniques are based, essentially, on the use of back emf's, through non-linear observers and adaptative systems with reference models [3] and [4]. Another possibility is the use of complete order state observers, like the Extended Kalman Filter [5].

In the method of using rotor saliency by signal injection, the difference between the d-q axis inductance is used, when it exists, like in the case of the interior permanent magnet motors and the inset magnets motors. This implementation can be accomplished through the injection of high frequency voltage components in all speed ranges [6]; however, in [7] the injection of these signals only for low speeds is proposed, using the fundamental component for speeds near rated speed.

This work proposes the implementation of a variable speed drive for a permanent magnet synchronous motor, substituting the position sensor by a position estimator, with a technique based in the use of phase voltages and currents, because the motor used doesn't present a representative difference between the d-q axis inductance; this characteristic can be clearly identified through high frequency signal injection. Therefore, a general method based on the position information acquired in the zero crossings, and crossings between themselves of the back emf's, was adopted. For the initial position detection, an adaptation of the algorithm proposed by [8] was made, and for the low speed operation, an open loop control algorithm was used. The open loop control was made, mainly, due to the little amplitude of the phase voltage signals and for consequence, of the back emf's calculated, and the presence of switching noises, produced by the low switching frequency, not completely filtered.

II. OPEN LOOP CONTROL ALGORITHM

For the implementation of the motor open loop control algorithm, it is necessary to detect the rotor initial position, which is more difficult in this work, due to the absence of a representative pole saliency in the motor, what limits the use of inductance variations in the classical form.

It is well known that for the operation in steady state, the available techniques are based in the direct or indirect use of the back emf's, but they only exist when the rotor is in movement. So, it was necessary to use another feature of the machine, to detect the rotor initial position and start the motor without the

occurrence of unwanted movements. The difference between the air gap distances in the magnetic circuits crossed by the d-q axis fluxes isn't representative to be used in the machine model, estimator implementation and controller. However, a detailed analysis of the motor allowed the detection of a small difference between these distances, which was smartly used to the detection of the initial position, because it provides small variations of the inductance with the position.
Using this feature, an algorithm was implemented, based on the proposal made in [8], which is based in the application of pattern pulses with pre-defined times, followed by the acquisition of the three-phase currents and using these values, to obtain the information of the initial position. It is valid to remind that to this implementation do not result in rotor's inadequate movements, it is necessary that the pulses be of short period of time, about 100 µs, such that they do not produce currents capable of generating torque.
Basically, three pulse types are applied, which are the result of the three switches configurations of the inverter, presented in the figure 2.1.

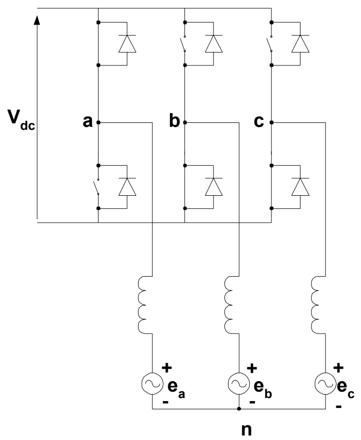


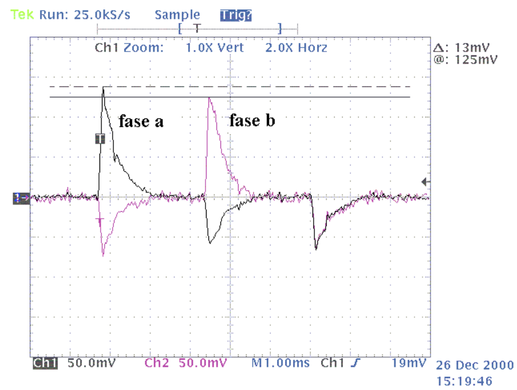
Figure 2.1: Switches configurations to the application of the pattern pulse 1: Phase a superior switch and phases b and c.

Using the pattern pulses, it is possible to define an approximated rotor positioning, through a simple decision algorithm, which compares the amplitudes of the currents ia, ib and ic, which are the result of the pattern pulses 1, 2 e 3, respectively. This algorithm is implemented by analogy to the implementation in [9], for a salient pole permanent magnet synchronous motor, which is based in the equation [2.1]. This equation is obtained by rearranging the voltage equation of a salient pole permanent magnet synchronous motor. However, in the present work, the equation [2.1] can't be used directly, because the q-axis inductance is a little bigger than the d-axis inductance, which is exactly the contrary of the represented by the equation [2.1]. The implementation proposed in [9], verify if the rotor d-axis is aligned with one of the three phases, since by the analysis of the equation [2.1], when the rotor d-axis is aligned with the a phase, for example, the θ angle is zero, therefore the phase a current variation in time is maximum.

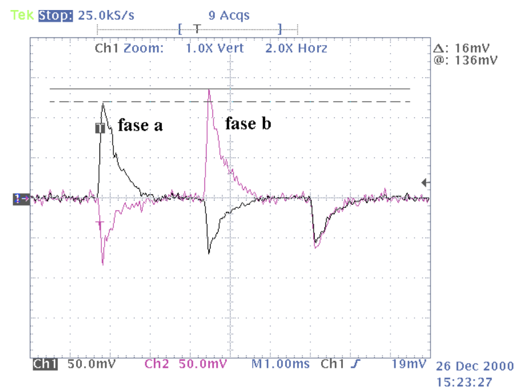
$$\frac{di_a}{dt} = \frac{4}{9}\frac{L_{g0} + L_{g2}\cos 2\theta}{L^2_{g0} - L^2_{g2}} V_{ab} \qquad [2.1]$$

Where:
L_{g0} corresponds to the invariant part of the inductance with the position and
L_{g2} corresponds to the variant part of the inductance with the position.

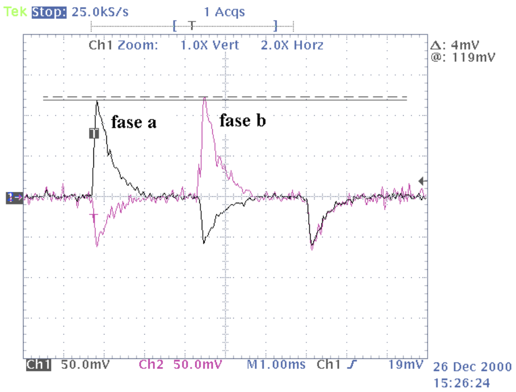
For the motor used in this work, it is verified that when the current variation in time is bigger to a certain phase, when compared to the other two phases, this phase is aligned with the rotor q-axis. So, the algorithm adopts as decision rule, exactly the opposite of the proposed by [9]. The current waveforms in the phases a and b, which result from the application of the three pattern pulses, are presented in the figure 2.2. It can be observed that it exists a representative difference between the amplitudes of the currents of the phases a and b, when rotor q-axis is aligned with one of these phases, as shown by figures 2.2 (a) and (b), with the phase current with which the rotor q-axis is aligned presenting bigger amplitude. However, when the rotor q-axis is aligned with the phase c, figure 2.2 (c), the difference between the phases a and b becomes extremely small, because in this situation the more representative difference appears in the phase c.



(a) Phase currents a and b, to the rotor aligned with the phase a.



(b) Phase currents a and b, to the rotor aligned with the phase b.



(c) Phase currents a and b, to the rotor aligned with the phase c.

Figure 2.2: Resulting phase currents a and b of the pattern pulses / scale: 100mV = 200mA.

The implemented algorithm decides if the rotor q-axis is near of the alignment with the phase which the current presents the biggest amplitude, to its respective pattern pulse. After this decision, to guarantee that the real and detected positions are equal, pulses are applied, also pattern, about 500 µs, in such a way to align the rotor q-axis with nearest stator magnetic pole. The validation of the decision algorithm was made through experimental results. With the rotor q-axis aligned with one of the three phases, it is possible, then, to drive the motor up to a certain speed, at which the back emf can be used to the position estimation, through the injection of sinusoidal three-phase currents in open loop, as the motor has the feature of sinusoidal flux distribution in the air gap. In this control algorithm, it was adopted the availability of rated torque, which imply in the injection of rated current, as a way to assure the synchronism, once most of the loads might be centrifugal or linear with the speed. So, the synchronism is assured, becoming the motor open loop drive the most general.

III. DRIVE USING THE ESTIMATED POSITION

The implementation of the estimator was accomplished using the back emf's zero crossing points and the crossing between themselves, obtained through the voltages, currents and parameters of the motor. As the back emf's of each phase are out of phase 90° of theirs respective d-axis, the information obtained through the back emf's is the position for the synthesis of currents in the three axis coordinate system (a, b e c), composed only by the rotor q-axis component. However, in the time intervals between these points there is no way to obtain directly the position information from the back emf's, as presented in figure 3.1.

To solve this problem, an algorithm based on counters was developed. These counters are triggered and blocked each time the software "passes" by a zero crossing of each phase.

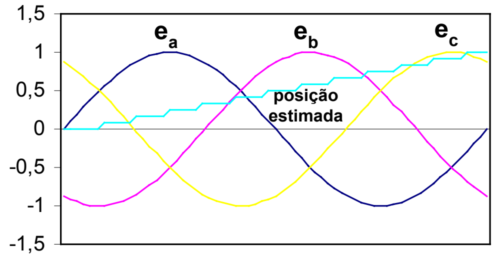


Figure 3.1: Position estimation cycle, using the representative points.

It is important to notice that each counter is triggered separately for each phase, for example, when occurs a zero crossing of the phase "a" with positive derivative, it is triggered a counter that is only blocked when same crossing is achieved in the next cycle. The same thing happens to the other phases, as presented in figure 3.2. The next step, having in a table the relation between the number of sampling intervals passed between a zero crossing and another, is to obtain the increment that has to be given to the estimated position, for each sampling interval.

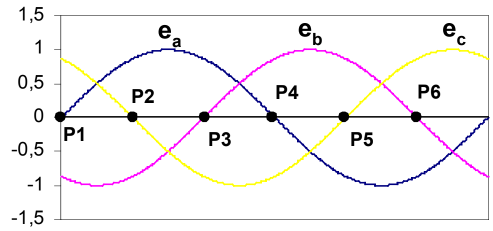


Figure 3.2: Trigger and block instants of the used counters.

The crossing points between the phases are neglected in this part, because the error introduced by the variation of the number of sampling intervals between them is bigger than the error caused by the variation of the number of sampling intervals between zero crossing points. The position estimation in one period, using the algorithm to obtain the position between the representative points, is shown in the figure 3.3, where is evident the estimation improvement, when compared with the estimation shown in the figure 3.1.

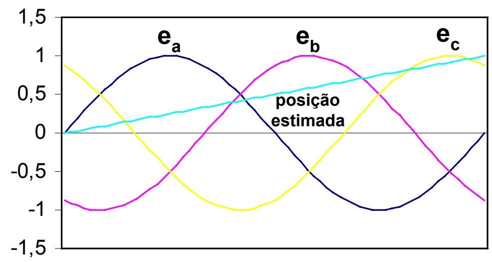


Figure 3.3: Position estimation cycle, using the algorithm to the estimation between the representative points.

Through the use of the estimated position, it is possible to implement the speed controller (PI control), based in the theory of synchronous motor control in field-coordinates [10]. The complete speed control system is presented in the figure 3.4.

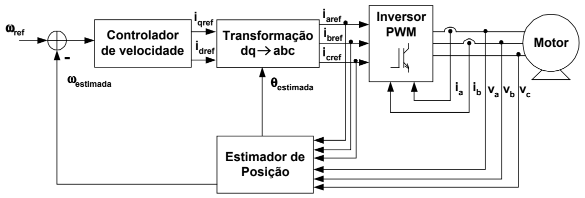


Figure 3.4: Complete speed control system.

IV. EXPERIMENTAL RESULTS

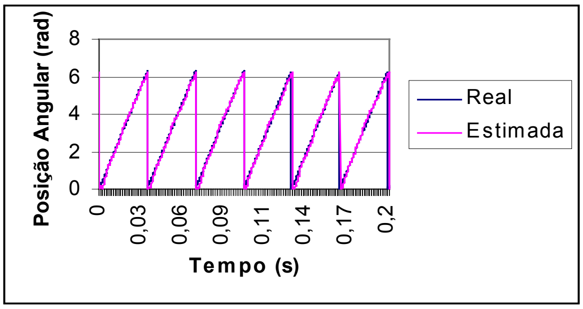
In this part the experimental results of the tests made, based in the proposed algorithms in the items 2 and 3, are presented. These results were obtained by the use of a development system for DSP's (*Digital Signal Processor*) of the Atlanta Signal Processors, Incorporated (ASPI), which basically consists, in a board with the DSP TMS320C25 and its peripherals, and the software to the system's installation. For the synthesis of the phase currents, a digital PWM with switching frequency of 6,6 kHz wa implemented.

The parameters of the used motor are presented in the table 4.1. The motor has 3 pairs of poles, surface mounted permanent magnets and is slotless.

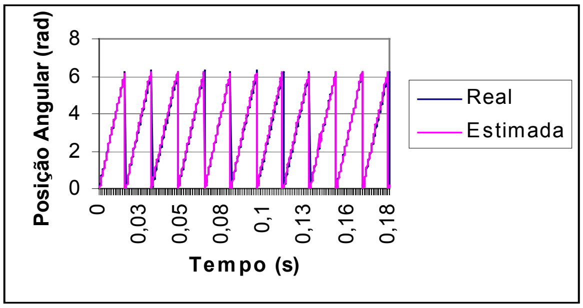
Table 4.1: Motor parameters.

Data	Values
Rated Voltage	127 V
Rated Current	1,6 A
Rated Torque	0,47 N.m
Rated Speed	5420 rpm
Efficiency	95%
Direct-axis inductance	1,621E-03 H
Quadrature-axis inductance	1,740E-03 H
Phase resistance	2,35 Ω
Flux Linkage	0,06 Wb
Moment of Inertia	200E-06 kg.m^2
Friction Factor	400E-07 kg.m^2.s

Initially, the tests for the verification of the estimation algorithm, comparing the rotor estimated position with the imposed position in open loop are presented. In the figure 4.1, are presented waveforms of these positions, where can be seen a convergence between the two signals, what indicates the correct operation of the estimator in its speed range (600 rpm up to 1200 rpm).



(a) Angular speed: 600 rpm.

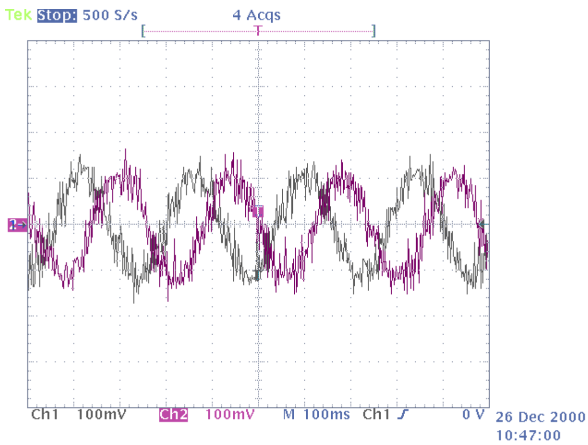


(b) Angular speed: 1200 rpm.

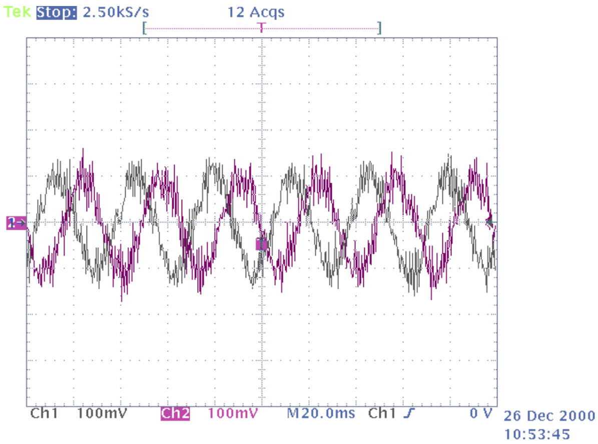
Figure 4.1: Imposed and estimated positions.

Additionally, tests were made for the acquisition of phase voltages and currents waveforms, considering several speed ranges, varying the load torque. The acquisitions were made after the speed stabilization, which implies in the motor operation in steady state.

Initially, are presented the waveforms of the phase currents "a" and "b" for the motor operation with the open loop algorithm in figure 4.2, which means, maintaining the amplitude of the current constant and without the use of the estimator.



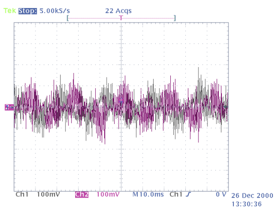
(a) Speed: 100 rpm.



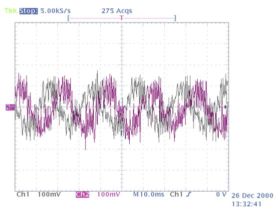
(b) Speed: 600 rpm.

Figure 4.2: Current waveforms of the phases a and b, without the estimator, with rated amplitude / scale: 50mV = 1A.

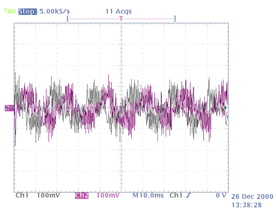
In the figure 4.3, are presented the currents waveforms of the phases "a" and "b" to the motor operation with the estimator, where can be noticed the speed controller actuation, varying the amplitude of the injected currents in the motor, according to the load torque variations.



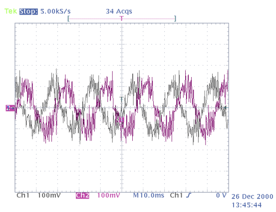
(a) Speed: 900 rpm.



(b) Speed: 900 rpm.



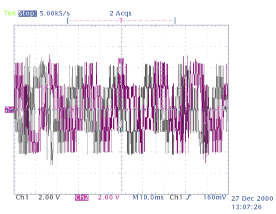
(c) Speed: 1200 rpm.



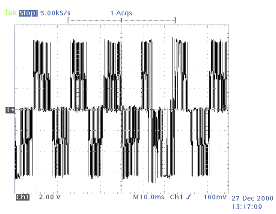
(d) Speed: 1200 rpm.

Figure 4.3: Current waveforms of the phases a and b, using the estimator / scale: 50mV = 1A. Without load (a) and (c) and with load (b) and (d).

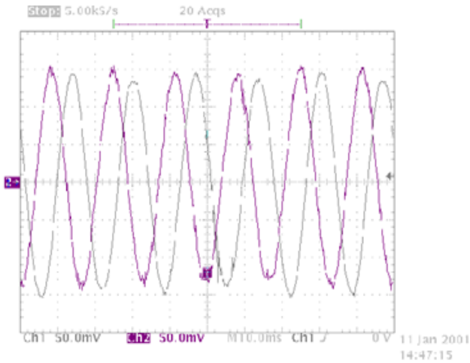
In the figure 4.4, the phase and line voltage waveforms are presented, before and after the analog filters (anti-aliasing).



(a) Phase voltages: 1200 rpm.



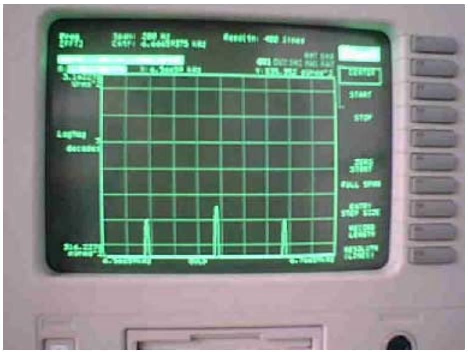
(b) Line voltage: 1200 rpm.



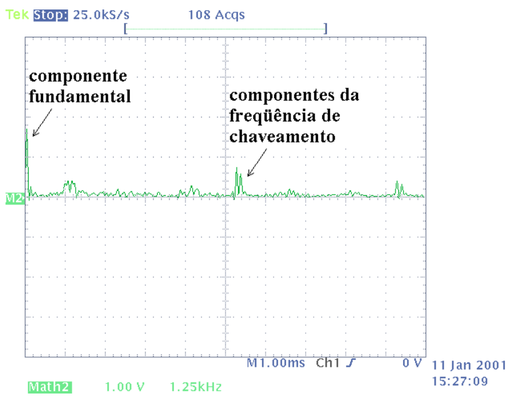
(c) Phase voltages: 1200 rpm.

Figure 4.4: Voltage waveforms of the phases a and b and line voltage waveform / scale: 1 = 10. Without filter (a) and (b) and with filter (c).

Finally, the currents and voltages frequency spectrums are presented in the figure 4.5.



(a) Detail of the components generated by the switching frequency in the phase a current, to 1200 rpm (60 Hz).



(b) Frequency spectrum of the phase a voltage signal, including the switching frequency, to 1200 rpm (60 Hz).

Figure 4.5: Currents and voltages frequency spectrums.

V. CONCLUSIONS

The elimination of the position sensor and the continuous decreasing cost of DSP allow the development of a low cost drive.

The initial position detection method implemented was tested for all the possible initial positions and has shown to be efficient.
The open loop control algorithm was implemented up to a limit speed (600 rpm), injecting currents with rated amplitude. Tests were made, increasing the rotor inertia momentum up to ten times. For all the tests the algorithm was efficient.
The chosen position estimation method, based in the indirect measurement of the back emf's, presented a good performance to this work and was robust in the used operation range (600 rpm up to 1200 rpm). The limitation of its operation range up to an inferior speed limit (600 rpm) appeared due to the synthesis incapability of currents with very little amplitude. Besides, the little amplitude of the phase voltage signals and for consequence of the back emf's calculated makes worth this limitation, because it becomes really difficult to calculate the back emf's crossing points due to the presence of switching noises not completely eliminated by phase voltage filters.
The work showed that it is possible to obtain a good performance for general applications of variable speed drives, using a permanent magnet synchronous motor without position sensor, implemented with a low cost digital system.

VI. ACKNOWLEDGEMENTS

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