AN EXPERIMENTAL PERFORMANCE EVALUATION OF A VECTOR-CONTROLLED INDUCTION MOTOR DRIVE SYSTEM

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***Abstract* – This work presents a performance evaluation of a vector-controlled induction motor. The evaluation is performed in both steady state and dynamic operation conditions. In steady state, the analysis is realized in terms of the experimentally obtained torque-speed curves. The transient conditions comprise sudden application and removal of the load (step change), where the motor speed behavior and response time are compared. Tests were performed for sensorless and with-encoder operation modes. The performance degradation due to motor parameter sensitivity is also evaluated**.

KEYWORDS

Vector Control; Induction Machine Drives; Parameter Sensitivity.

I. INTRODUCTION

Converter-fed induction motors represent nowadays a widespread solution. In applications where an optimum dynamic behavior and/or high torque peaks are needed, the vector control emerges as a very effective solution. Although the technique of the field orientation arised in the early 70's, only in the last decade the converters operating under this control strategy were introduced to the high volume, low power market [1].

The literature related to this subject is extremely vast; in order to provide a brief background, some works can be mentioned. The principles of this control method have been extensively discussed, as in [2,3,4]; a diversity of different alternatives of its implementation have been proposed [5,6,7,8], the motor parameter sensitivity of the vector control was evaluated [9,10] as well as schemes [11,12,13,14] for adapting these parameters in order to assure the high performance of this control strategy.

However, despite the plenty of works that have already been published, this paper brings a different and more practical approach. Here, the contribution is to present a set of experimental tests and results that are very useful in helping the engineers to decide which drive system better fulfill the requirements of their particular industrial applications and show what can be expected in terms of performance from each one. In fact, commercial converters can be very different from the prototypes used in the scientific works found in the literature; since there is a more serious concern related to costs and also the fact that the flexible systems commercially available are not so precisely tuned as the former, the performance of these equipment can be very different from the optimized ones found in the papers. Results will show that in some situations the vector controlled motor drive can present a performance similar to a V/f converter, which is much more cheaper and simpler.

II. DESCRIPTION OF THE SYSTEM UNDER TEST

The converter used in the tests is a commercially available one, and makes use of the field orientation strategy. It presents a speed closed loop control that can operate using an encoder to provide the speed information or in the sensorless mode, where the speed is internally estimated. The converter adopts PWM technique at a switching frequency of 5 kHz.

The vector control technique is naturally machine parameter dependent, although each implementation scheme presents its particular sensitivity to the motor parameters. In order to calculate the orthogonal components of the stator current vector responsible for flux and torque production, the vector controller requires the parameters of the machine to perform its internal algorithm. In relation to these information, the vector-controlled converter used in this work has a self-tuning routine which, by means of measurements and calculations, automatically estimates these parameters. Alternatively, this information can be manually provided to the equipment, requiring its previous knowledge.

The induction motor used in the tests has the following characteristics: 1,5 hp, 220/380 V, 5/2,89 A, 1690 rpm.

Step Load Changes and Speed Measurement

In order to perform sudden applications and removal of load at the motor axis, a current-controlled chopper was built and connected in series with the armature of a d.c. machine. With a current rising time as short as 2 ms, the torque variations produced by the d.c. machine could be considered as "step changes".

For the speed measurement, the pulses of the encoder connected to the motor were sent to a microcomputer (PC), where a specially developed program was used to calculate the rotor speed.

Figure 1 shows the experimental setup.

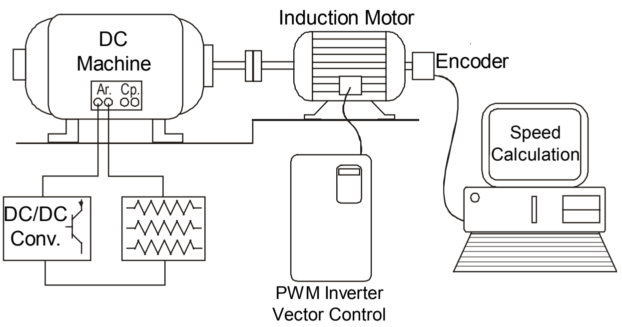

Figure 1: Experimental setup for the tests.

III. EXPERIMENTAL PROCEDURE

The tests were performed according to the following procedure:

a) Evaluation of the motor performance under dynamic conditions, operating in the sensorless mode: in this situation, the performance of the drive running with the parameters provided by the self-tuning was compared to its performance when operating with the parameters manually set, obtained from no-load and rotor-blocked tests.

b) Evaluation of the motor performance under dynamic conditions, operating with the parameters manually inserted (obtained from tests): in this situation, the performance of the drive operating with the encoder (speed measurement) was compared to it in the sensorless mode (speed estimation).

c) Performance evaluation in steady-state: here, the torque-speed curves were obtained with the drive operating with encoder and in the sensorless mode, using the estimated parameters (by the converter) and the manually provided ones (from tests). The torque production capability and speed regulation were then compared for each of these operation modes.

In items a) and b) described above, the motor was initially running at no-load. The load is then applied and removed few seconds latter, according to table I.

TABLE I
Analyzed cases in the dynamic tests

Case number	Reference speed (rpm)	Applied Load (N.m)	% of the motor nominal torque
1	1800	6,24	100 %
2	1500	5,00	80 %
3	600	3,74	60 %

As further information, results obtained under the operation of a *V/f* control converter were also included.

IV. RESULTS

Dynamic performance of the drive in the sensorless mode (item "a")

Here, the performance of the drive running with the parameters provided by the self-tuning was compared to its performance when operating with the parameters manually set. The results obtained for case number 1 are shown in figure 2. The curve in blue represents the motor speed for the operation with the parameters experimentally obtained; the one in black is related to the operation with the parameters estimated by the converter self-tuning. From the observation of figure 2, the worse performance of the drive when operating in the latter case can be promptly noted.

In fact, the estimated values of the motor parameters are considerably different from the ones obtained in the tests. As the latter had already been verified, there was an expectation that the former would be mistaken, and this fact was even more highlighted when the degradation in the performance was detected. Table II shows the correct and the estimated values of the motor parameters.

TABLE II
Motor Parameters required by the control

Parameters	R_S (Ω)	τ_R (ms)	I_M (A)	σ_R (mH)
From Tests	2,6	65,1	2,9	4,36
Self-tuning	2,6	156,0	2,4	12,0

Where R_S is the stator resistance; τ_R is the rotor time constant; I_M is the magnetizing current; σ_R is the rotor leakage inductance.

From figure 2, one can note that the operation with the estimated parameters results in a small speed error in steady state at no-load, about 10 rpm (black curve), which does not happen with the experimental parameters (blue curve).

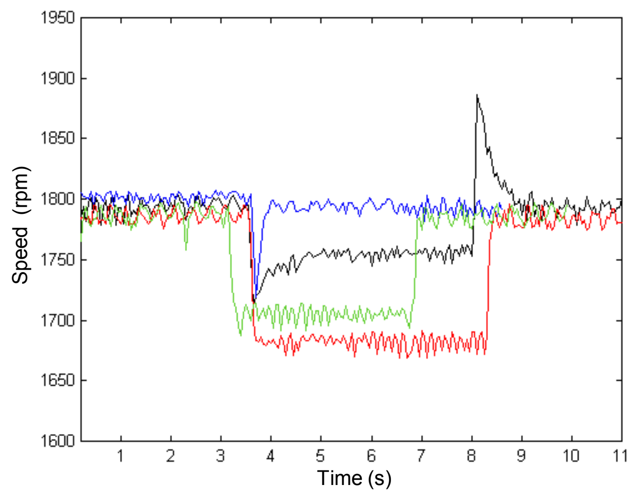

Figure 2: Motor speed behavior under step load changes for different operation modes – case 1. In blue: experimental obtained parameters; in black: estimated parameters by the converter; in red: operation under V/f control; in green: operation without a frequency converter.

It can be observed from the blue curve that when the load is suddenly applied, the speed decreases about 80 rpm in 120 ms and takes more 300 ms to reach reference speed, resulting in a total response time of approximately 420 ms. From the black curve, it can be seen that, although the initial decrease in the speed for the step load change is similar to the case mentioned above, the motor is not able to reach the reference; more than one second is necessary to attain the new steady state speed, equal to 1750 rpm. Thus, a speed steady error of 50 rpm is presented.

The behavior of the speed in the load removal could not be registered for the manually set motor parameters operation. Due to the transient positive peak, the speed overtook 1900 rpm and the motor started a generating operation, rapidly increasing the converter DC link voltage and disabling the drive, as a protection. For cases similar to this one, a breaking resistor should be used connected to the converter capacitor.

For the case of operation with the motor parameters estimated by the converter, when the load is removed the speed reach values up to 1890 rpm in 100 ms, taking about one more second to reach back the reference. Hence, considering these two operation cases, it is clear the influence exerted by the precise information of the motor parameters provided to the control, being crucial for the drive performance. Mistaken parameters have lead to an overall performance degradation, resulting in steady state speed errors and long time responses. This also indicates that the parameter estimative process of the converter is not very effective; the industry technical personnel should run the proper tests and calculate the motor parameters rather then using the ones provided by the converter algorithm, otherwise the good performance of the vector control will not be assured. As further information, curves in red and in green represent the motor operation with a V/f converter and with no converter, respectively. As expected, due to the lack of a speed feedback control, when rated load is applied, the speed decreases to the rated value, 1700 rpm. With the converter, it stabilizes in a little lower speed value. This may be occurring because of the additional losses in the motor due to the harmonic content of the voltage supplied to the motor, which, in 60 Hz, present low-order components due to overmodulation.

The results obtained for cases 2 and 3 are presented in figures 3 and 4, respectively. Since these results have shown to be quite similar to the ones corresponding to case 1 (figure 2), additional comments are not necessary.

Dynamic performance of the drive with the manually set parameters (item "b")

Here, the performance of the drive operating with the encoder (speed measurement) was compared to it in the sensorless mode (speed estimation); in both cases the drive was provided with the motor parameters experimentally obtained.

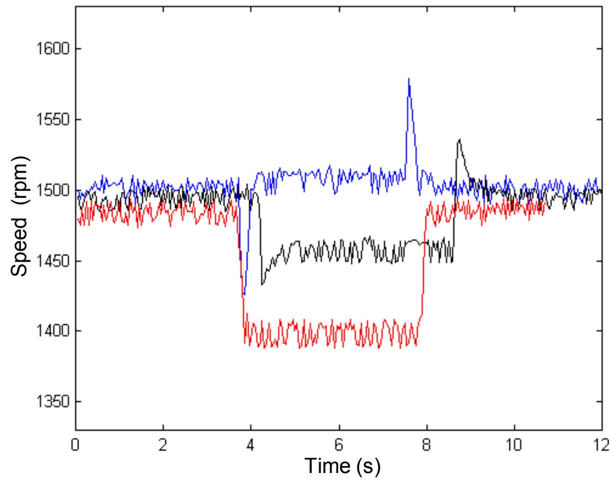

Figure 3: Motor speed behavior under step load changes, for different operation modes – case 2. In blue: experimental obtained parameters; in black: estimated parameters by the converter; in red: operation under V/f control.

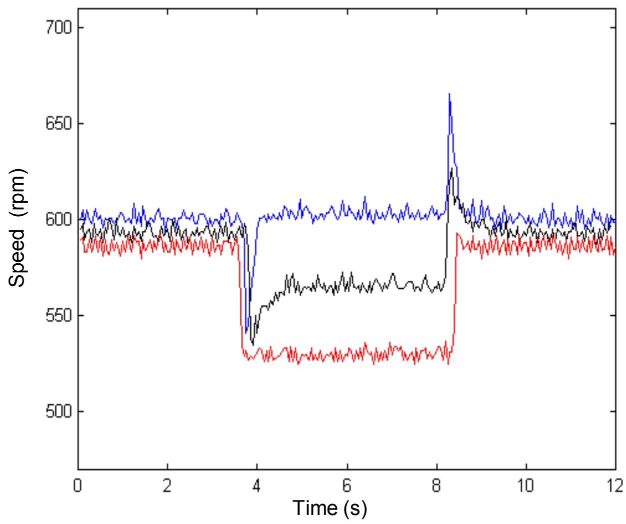

Figure 4: Motor speed behavior under step load changes, for different operation modes – case 3. In blue: experimental obtained parameters; in black: estimated parameters by the converter; in red: operation under V/f control.

The results related to case number 1 is shown in figure 5. After the application of the load, a small steady state speed error can be observed in the sensorless operation (black curve).

The response time for both operation modes was equivalent, although the operation with encoder (blue curve) resulted in lower peaks during load transitions. The sudden removal of the load during sensorless operation resulted in the actuation of the capacitor overvoltage protection, as mentioned previously in this paper. Besides the lower speed peaks during the load changes and zero steady state speed error, the operation with the measurement of the speed also assured better time responses (250 instead of 400 ms), particularly in cases 2 and 3, shown in the sequence (figures 6 and 7).

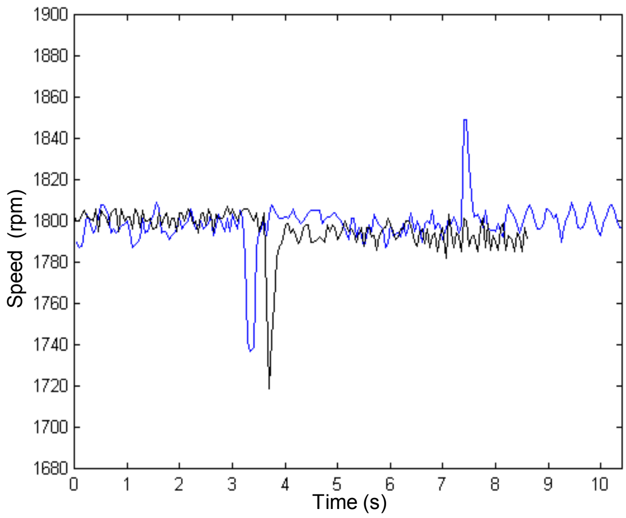

Figure 5: Motor speed behavior under step load changes, for different operation modes – case 1. In blue: operation under speed measurement, by an encoder; in black: speed estimation (sensorless mode).

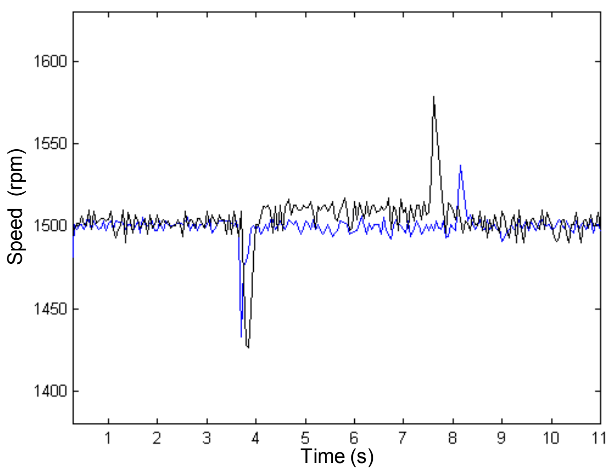

Figure 6: Motor speed behavior under step load changes, for different operation modes – case 2. In blue: operation under speed measurement, by an encoder; in black: speed estimation (sensorless mode).

Motor steady state performance

In this item the torque-speed curves of the motor are obtained under the following operation modes :

a) Operation under vector control, with speed measurement, using the experimentally obtained motor parameters;
b) Operation under vector control, in the sensorless mode, using the experimentally obtained motor parameters;
c) Operation under vector control, in the sensorless mode, using the parameters from the converter self-tuning.
d) Operation under scalar *V/f* control.

Figures 8, 9, 10 and 11 show the results.

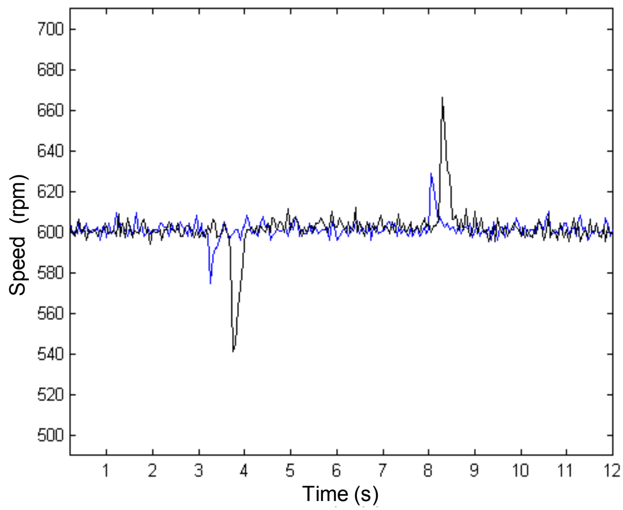

Figure 7: Motor speed behavior under step load changes, for different operation modes – case 3. In blue: operation under speed measurement, by an encoder; in black: speed estimation (sensorless mode).

The examination of figure 8 reveals the excellent steady state performance of the motor under the conditions described in “a”. There are high torque peaks and precise speed regulation. At 90 rpm, for instance, a peak torque of 3.8 p.u. was registered, with the speed strictly fixed at the reference value. At this operation point, a 3.2 p.u. current was imposed to the motor, with a frequency of 16.3 Hz, which results in a large motor slip. Torque peaks so high as the ones depicted in figure 8 occur because the vector control assures rated flux in the machine, leading to high torque/current ratios. Under constant flux, the motor torque becomes proportional to the motor slip. Just for a comparison, a typical N category induction motor produces at start a torque about 1.5 p.u. with 6 p.u. of stator current. Here, at 3 Hz, a 3.8 p.u. torque was produced with just 3.2 p.u. of current.

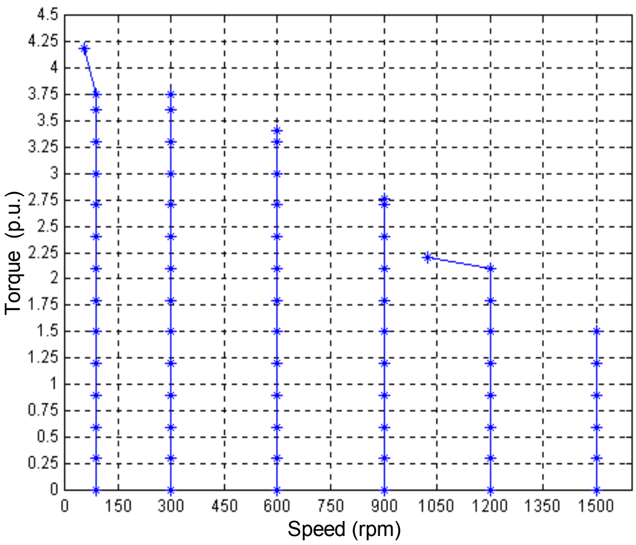

Figure 8: Motor torque-speed curves under vector control, measurement of speed (encoder) and using the experimentally obtained motor parameters.

The obvious reason is that, in the former case, the rotor flux is much lower that the rated (no-load) one, while in the latter the flux is kept nearly the rated value.

From figure 9, which represents the results for the case "b", a large reduction in the peak torques, especially in lower frequencies, as well as a considerable degradation in speed regulation, can be promptly observed.

Figure 10 shows the results for the motor operation in the sensorless mode and using the motor parameters from the self-tuning (case "c"). The peak torques and speed regulation became even worse.

Figure 11 depicts the operation under V/f control. Obviously, since this operation mode does not present speed control, as the applied torque is increased, the speed decreases, following the working principle of the induction machine, resulting in a poor speed regulation. As the load increases, the slip frequency becomes higher and the flux level reduces, leading to lower torque peaks.

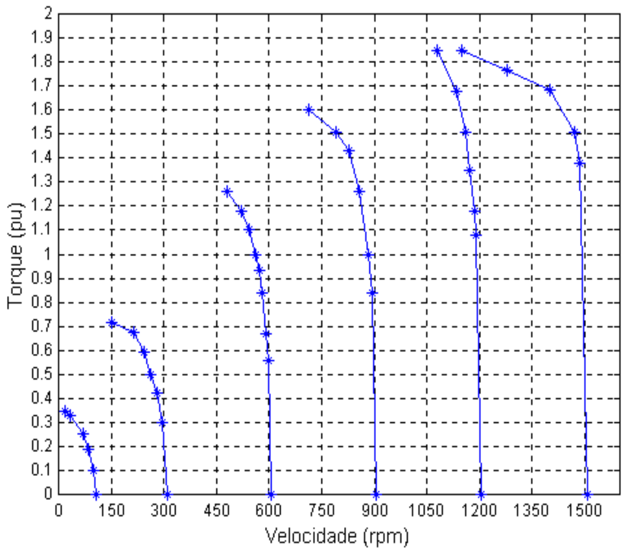

Figure 9: Motor torque-speed curves under vector control, sensorless operation and experimentally obtained parameters.

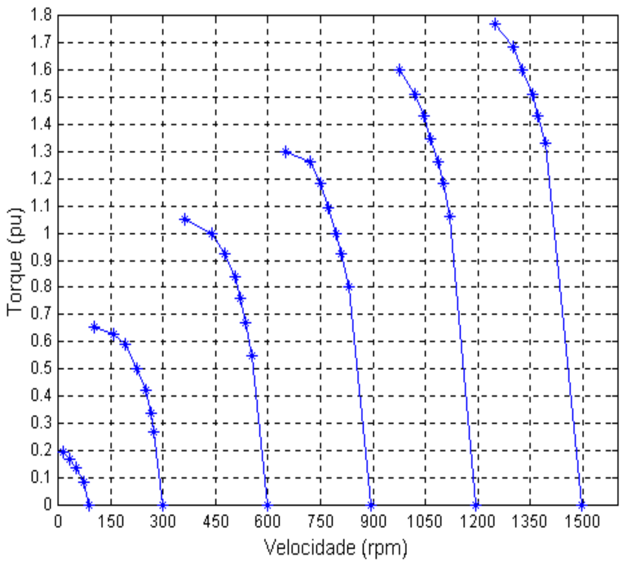

Figure 10: Motor torque-speed curves under vector control, sensorless operation and motor parameters obtained from the converter self-tuning.

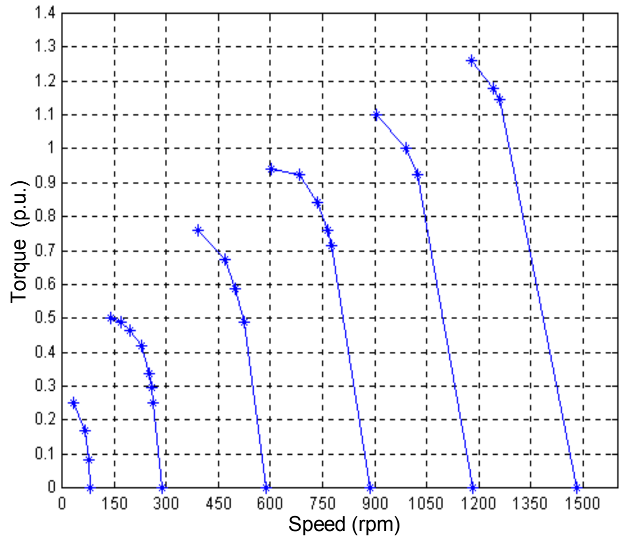

Figure 11: Torque-speed curves for operation under V/f control.

V. CONCLUSION

An experimental evaluation of a vector controlled induction motor drive system was performed, for dynamic and steady state conditions and for different operation modes.

It was observed that the operation with speed measurement (with encoder) instead of its estimation (sensorless mode) improves the motor dynamic performance, decreasing the amplitude of speed peaks in load variations and bringing some reduction in the response time. However, in steady state, particularly in the torque production and speed regulation, the operation with encoder showed to be even more superior, especially in lower frequencies. Nevertheless, for the equipment used in this work, the cost of the converter additional board and the encoder required to operate under speed measurement is equivalent to 60 % of the converter itself, thus the industry engineer should evaluate its cost-benefit and check which configuration best fits and fulfill the requirements of his particular application, based on the results presented here.

The vector control strategy is motor parameter dependent. Deviations in the values provided to the control lead to performance degradation. In this work this sensitivity was evaluated. The parameter estimation algorithm of the converter showed to be not very effective. Using these mistaken parameters the overall performance of the drive becomes much worse. Under this condition, the control is not able to properly calculate the torque and flux components, since there is no more total decoupling between them.

REFERENCES

[1] W. Drury, "The Variable Speed Drives Market – Past, Present and a View on the Future", *International Conference on Electrical Machines*, pp.1, vol. 1, 1998.

[2] E. T. T. Ho, P. C. Sem, "Decoupling Control of Induction Motor Drives", *IEEE Transactions on Industrial Electronics*, vol. 35. n. 2, pp. 253-262, 1988.
[3] R. W. De Doncker, D. W. Novotny, "The Universal Field Oriented Controller", *IEEE Transactions on Industry Applications*, vol. 30, nº 1, January/February 1994.
[4] D. A. Andrade, A. Hughes, J. Corda, "Principles of Vector Control in Cage Motors: an Easy Quantitative Approach via Space Phasor", *IEE Conference Publications on Power Electronics and Variable Speed Drives*, n. 399, pp. 204-210, London, October, 1994.
[5] M. Koyama, M. Yano, I. Kamiyama, S. Yano, "Microprocessor-Based Vector Control System for Induction Motor Drives with Rotor Time Constant Identification Function", *IEEE Trans. on Industry Applications*, vol. IA-22, n. 3, May/June 1986.
[6] T. Ohtani, M. Takada, K. Tanaka, "Vector Control of Induction Motor without Shaft Encoder", *IEEE Transactions on Industry Applications*, vol. 28, n. 1, January/February 1992.
[7] X. Xu, D. W. Novotny, "Implementation of Direct Stator Flux Orientation Control on a Versatile Digital Signal Processor System", *IEEE Transactions on Industry Applications*, vol. 27, n. 4, July/August 1991.
[8] J. W. L. Nerys, A. Hughes, J. Corda, "Alternative Implementation of Vector Control for Induction Motor and Its Experimental Evaluation", *IEE Proc. – Electr. Power Appl.*, vol. 147, n. 1, January 2000.
[9] R. Krishnan, F. Doran, "Study of Parameter Sensitivity in High Performance Inverter-Fed Induction Motor Drive Systems", *IEEE Transactions on Industry Applications*, vol. IA-23, n. 4, July/August 1987.
[10] K. B. Nordin, D. W. Novotny, D. S. Zinger, "The Influence of Motor Parameter Deviations in Feedforward Orientation Drive Systems", *IEEE Transactions on Industry Applications*, vol. IA-21, n. 4, July/August 1985.
[11] C. Wang, D. W. Novotny, T. A. Lipo, "An Automated Rotor Time Constant Measurement System for Indirect Field-Oriented Drives", *IEEE Transactions on Industry Applications*, vol. 24, n. 1, January/February 1988.
[12] C. C. Chan, H. Wang, "An Effective Method for Rotor Resistance Identification for High-Performance Induction Motor Vector Control", *IEEE Transactions on Industrial Electronics*, vol. 37, n. 6, December 1990.
[13] L. C. Zai, C. L. Demarco, T. A. Lipo, "An Extend Kalman Filter Approach to Rotor Time Constant Measurement in PWM Induction Motor Drives", *IEEE Transactions on Industry Applications*, vol. 28, n. 1, January/February 1992.
[14] R. J. Kerkaman, B. J. Seibel, T. M. Rowan, D. W. Schelegel, "A New Flux and Stator Resistance Identifier for AC Drive Systems". *IEEE Transactions on Industry Applications*, vol. 32, n. 3, May/June 1996.