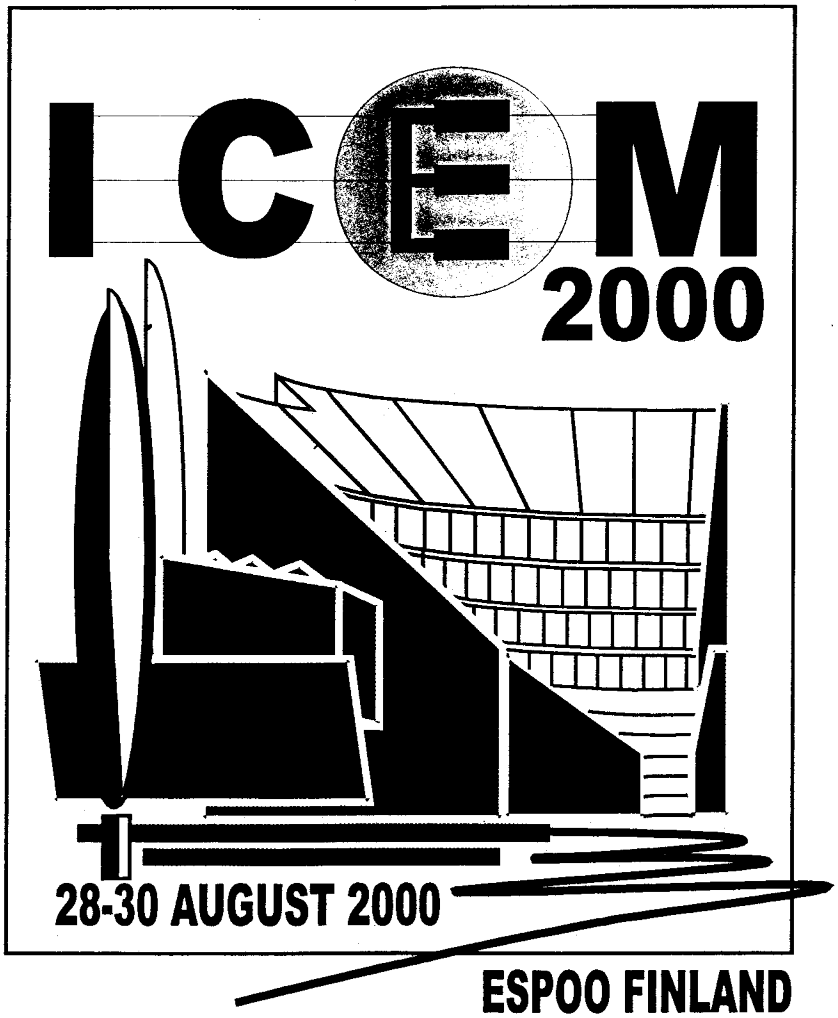
INTERNATIONAL CONFERENCE
ON
ELECTRICAL MACHINES



HELSINKI UNIVERSITY
OF TECHNOLOGY

ESPOO FINLAND

ICEM 2000 Proceedings

Volume II

International Conference on Electrical Machines

28 – 30 August 2000

Organised by Laboratory of Electromechanics,
Helsinki University of Technology, Finland

Helsinki University of
Technology
Espoo Finland

Direct Torque Control of the induction machine using field oriented method and time frequency transformation for speed estimation and parameter adaptation

J. A. Restrepo
J. M. Aller

T. Pagá
V. M. Guzmán

A. Bueno
M. I. Giménez

Universidad Simón Bolívar
Grupo SIEP, Lab C.
Valle de Sartenejas, Baruta, Edo. Miranda
Caracas, Venezuela
Telephone +58 2 9064012
Fax +58 2 9063712

ABSTRACT

In this paper, a Direct Torque Control (DTC) scheme for the induction machine is presented. The rotor speed estimation is performed using the field oriented model. Time frequency spectral methods are studied for accurate speed estimation, using the stator current information. Combining these estimation techniques, a precise T_r adaptation in real time is expected. The proposed method reduces controller dependence on the induction machine model parameters, and removes the need for speed sensor in the mechanical shaft.

Keywords: DTC, speed estimation, induction machine, field oriented transformation, time-frequency.

1 INTRODUCTION

During the last decade, induction machine control using space vectors and field oriented transformations has been thoroughly developed [1]. With this technique, the AC machine speed and position controllers have reproduced the DC machine control behavior. The control's method main limitation is due to the transformation's dependence on machine model parameters. Many authors [2][3][4][5][6][7][8] have proposed estimation strategies and real time parameter adaptation techniques to reduce controller problems and to increase the system's dynamic performance. The speed and position controls require speed or position feedback. For this purpose, it is common to use mechanical sensors directly coupled to the rotor shaft. In the last decade, many authors have centered their efforts in solving the rotor speed-measuring problem without mechanical sensors [9][10][11]. Some methods perform state estimation using the actual electric variables' value and the machine model parameters [9], rendering a reduced precision due to parameters variation with temperature or saturation. Current harmonics, produced by the presence of stator and rotor slots or by the dynamic and static eccentricities, contain information about the rotor speed. Therefore, other speed estimation methods are based on the stator current spectral analysis [10]. The first spectral based methods used FFT techniques, but these methods do not give useful information during speed transients, and a more complex method is required. In a previous work, the use of the time-frequency transformation to determine the mechanical speed during the dynamic operation has been proposed [11]. The speed estimation using spectral methods do not depend on the machine model parameters, but the processing load is too high even for advanced processors.

In this work, the sensorless speed detection using state estimators and spectral analysis is achieved. A field oriented model is used to determine the rotor speed during dynamic operation, and the time-frequency transformation is used to adjust the rotor time constant during the steady state. This combination allows for real time rotor time constant calculation and reduced errors in rotor speed estimation. A high dynamic performance system can be obtained coupling this speed estimation method to DTC, without mechanical sensors coupled to the machines shaft. The proposed control scheme and the speed estimation method have been modeled in order to verify the theoretical predictions. An experimental DSP based platform was developed to check the system dynamic performance. Experimental results are shown to illustrate the control's scheme behavior.

2 DIRECT TORQUE CONTROL

A DTC system is based on the direct measurement and regulation of the instantaneous electric torque. For this purpose, actual voltage and current measurements must be performed in the machine terminals. The stator flux linkage is obtained by integrating the electromotive force in the stator winding, as follows:

$$\vec{\lambda_s} = \int_0^t \left(\vec{v_s} - R_s \vec{i_s} \right) dt' \tag{1}$$

where,

$$\vec{x_s} = \sqrt{\frac{2}{3}} \left[1 \; e^{j\frac{2\pi}{3}} \; e^{j\frac{4\pi}{3}} \right] \cdot \left[x_{as}(t) \; x_{bs}(t) \; x_{cs}(t) \right]^t \qquad \forall x \in \{v,\ i,\ \lambda\} \tag{2}$$

The electric torque is obtained multiplying the stator flux linkage and the stator current space vectors:

$$T_e = \vec{\lambda_s} \times \vec{i_s} = \left(L_s \vec{i_s} + L_{sr} \vec{i_r^s} \right) \times \vec{i_s} = L_{sr} \vec{i_r^s} \times \vec{i_s} \tag{3}$$

where:

$$\vec{i_r^s} = \vec{i_r} e^{j\theta} \tag{4}$$

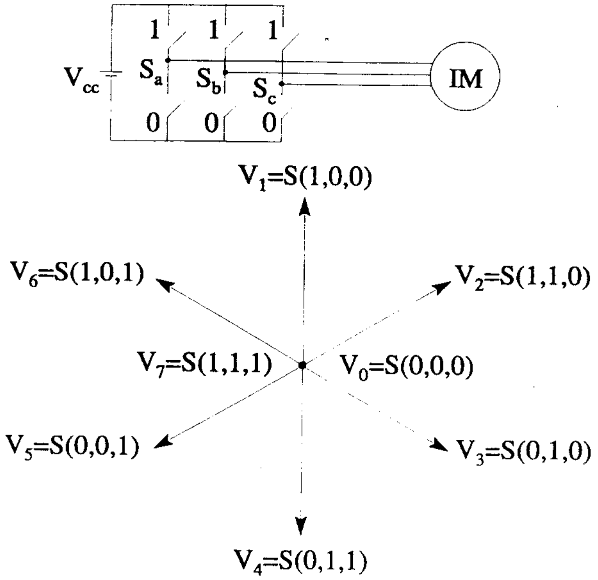


Fig.1 Voltage space vectors as function of the inverter connectivity.

The only machine parameter involved in Eq. (1) is the stator resistance R_s. The errors introduced by this parameter variation due to the temperature are small and can be reduced using real time parametric estimation.

With respect to the stator voltage, an inverter bridge can produce only eight different states. Each state defines the voltage space vector applied to the stator windings. Six of this bridge states are constant magnitude vectors with a $\pi/3$ phase lag between them. The other two states are associated with the null space vector. These eight voltage space vectors can be defined as a function of the bridge connectivity state, as shown in Fig. 1.

In order to adjust the electric torque and the stator linkage flux, the DTC algorithm chooses the stator voltage space vector that maximizes the required change. When the torque reference is inside a hysteresis band, the null voltage vector producing by the smallest number of bridge commutations is chosen [7].

The DTC strategy is shown in figure 2. Flux-Linkage can be adjusted to rotate clockwise or counter-clockwise, and also to increase or decrease in magnitude to fit the torque reference. Each one of the six zones drawn in this figure has a different bridge connectivity selection to perform these strategies. The space voltages corresponding to the zone where the linkage flux is located, or in the opposite zone, are not used to change the electric torque or the flux linkage magnitude.

Using DTC, a more robust speed or position control of the induction motor can be developed [8]. Figure 3 shows a block diagram implementation of this control. The adaptive estimator is used to determine the zone where the flux-linkage is positioned, as well as the instantaneous electric torque, the mechanical speed and the flux-linkage magnitude.

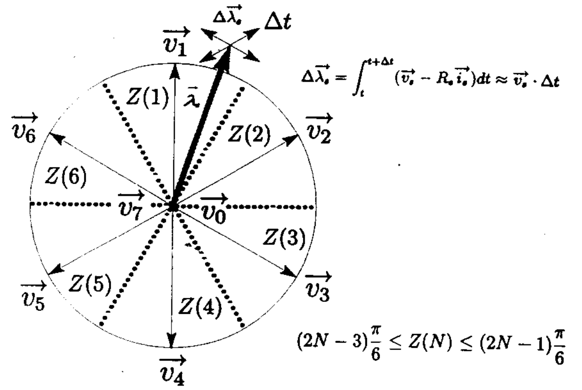


Fig.2 Change of the linkage flux using the voltage space vectors of the stator.

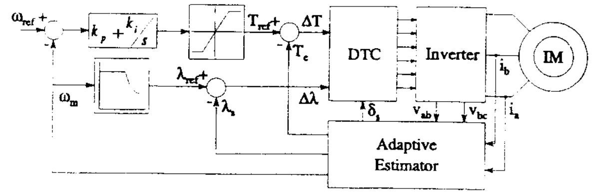


Fig. 3 Speed controller of the induction machine using DTC control and adaptive estimator.

3 ROTOR SPEED ESTIMATION

During dynamic operation, a field oriented model is used for fast speed estimation. In order to perform this estimation the flux and the electric torque must be known, to calculate the magnetizing current and the quadrature stator current (i_{sq}), which are the variables required to determine the speed.

This calculation is highly dependent on the rotor time constant, T_r. Therefore, it is necessary to tune the T_r values. To perform this, the same expression used for speed estimation is used, but in this case a precise speed measurement is required. this is achieved using a time-frequency method, described below.

3.1 *Electric torque and flux estimation*

Figure 4 shows the procedure used to calculate the flux linkage and the electric torque. With these variables it is possible to obtain the estimated rotor speed.

3.2 *Speed estimation using field oriented model*

Several reference frames can be used to estimate the rotor speed. The field oriented model is used to perform this

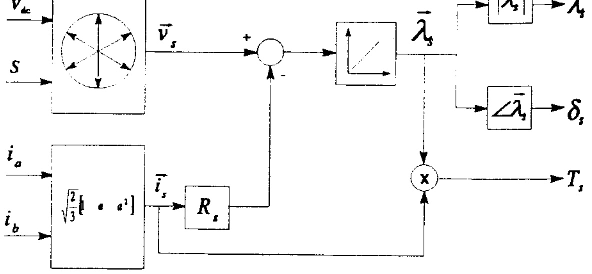


Fig. 4 Electric torque and linkage flux estimator.

task efficiently. In this model, the magnetizing current is defined as:

$$\vec{i_m} \equiv \vec{i_s} + \frac{L_r}{L_{sr}}\vec{i_r^s} = \vec{i_s} + \frac{L_r}{L_{sr}}\vec{i_r}e^{j\theta} \tag{5}$$

Using this equation, the stator flux can be expressed as:

$$\vec{\lambda_s} = L_s\vec{i_s} + L_{sr}\vec{i_r^s} = \hat{L}_s\vec{i_s} + \frac{(L_{sr})^2}{L_r}\vec{i_m} \tag{6}$$

From Eq. (6), the magnitude i_m and the spatial position of the magnetizing current can be calculated, using the flux linkage obtained by equation (1). The electric torque in a field oriented model can be written as follows:

$$T_e = \frac{(L_{sr})^2}{L_r} i_m \cdot i_{sq} \tag{7}$$

The rotor speed can be obtained form the standard field-oriented equation:

$$\dot{\theta} = \omega_m = \dot{\delta} - \frac{i_{sq}}{i_m T_r} \tag{8}$$

where $\dot{\delta}$ (the magnetizing rotational speed) can be obtained from:

$$\dot{\delta} = \frac{(i_{mx}\frac{di_{my}}{dt} - i_{my}\frac{di_{mx}}{dt})}{i_m^2} \tag{9}$$

Figure 5 shows the resulting speed estimator diagram.

3.3 Rotor time constant adaptation

The main error introduced in equation (8) is due to rotor time constant temperature variations, during operation. Inductive parameters are practically constant. In a non-precise speed control, this expression can be used as a speed measurement. When more precision is required, an adaptive estimator can be used. With the spectral information obtained from the stator spatial current, the slip can be calculated when necessary. This variable can be used to estimate a precise value for the rotor time constant T_r. The time-frequency transformation [12], can be used to perform this calculation during transient operation. This time-frequency algorithm is used only when the machine internal temperature changes the rotor resistance. In any other time, Eq. (8) is employed in the speed estimation process. Figure 6 shows the rotor time constant adaptation block diagram using the spectral slip detector.

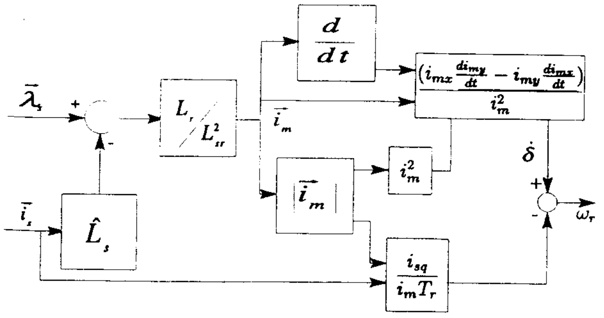


Fig.5 Rotor speed estimation.

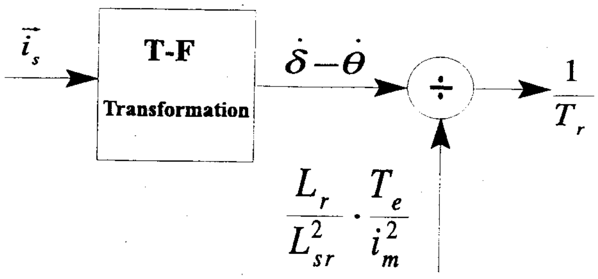


Fig.6 Adaptation of the rotor time constant T_r.

3.4 Time-frequency transformation

Some of the methods proposed to measure the rotor speed in squirrel-cage induction machines, without the use of shaft mounted sensors and non-dependent of machine parameters, are based on the analysis of speed related stator-current harmonics. Some algorithms proposed in previous works use the Wigner Distribution (WD), the Exponential Distribution and the Instantaneous Power Spectrum (IPS) [11][13], to retrieve the speed related information present in the AC machine stator current. The rotor speed can be inferred from an interpretation of the stator current harmonics [14][10].

Representation of signals in the Time-Frequency (TF) domain has proved to be useful in the analysis of non-stationary processes, as for example speech, seismic, and radar signals. The Short Time Fourier Transform (STFT) is the more commonly used Time-Frequency distribution, with a recent increase in the use of the Wigner-Distribution (WD). The cross-WD of the signals f(t) and g(t) is defined as:

$$WD_{f,g}(t,\omega) = \int_{-\infty}^{\infty} f(t+\frac{\tau}{2}) \cdot g^*(t-\frac{\tau}{2}) \tag{10}$$

Cohen [15] introduced a more general representation for time-frequency distributions, commonly referred as Generalized Time Frequency Distributions GTFD. They are described by the following equation:

$$D(t,\omega:\phi) = \frac{1}{4\pi^2}\iiint e^{j(\xi\mu-\tau\omega-\xi t)}\phi(\xi,\tau)f(t+\frac{\tau}{2})f^*(t-\frac{\tau}{2})d\mu d\tau d\xi \tag{11}$$

where $f(\mu)$ is the time signal, $f^*(\mu)$ is its complex conjugate, and $\phi(\xi,\tau)$ is the transformation's kernel. A problem with the WD is the appearance of interference terms or cross-terms, also known as artifacts. Different TF distributions have been proposed which try to address the problem of reducing the interference terms' magnitude, while satisfying some marginal properties. Depending on the selected kernel, different types of distributions appear, e.g. Wigner, Page, Sinc, Exponential, etc. Using a new variable, $v = \xi - t$, and integrating over ξ, Eq. (11) can be rewritten as:

$$D(t,\omega:\Phi) = \frac{1}{2\pi}\iint \Phi(v,\tau)f(v+t+\frac{\tau}{2})f^*(v+t-\frac{\tau}{2})e^{j\omega\tau}dvd\tau \tag{12}$$

Where $\Phi(v,\tau)$ is the transformed kernel.

For practical implementation of distributions members of Cohen's class, the generalized discrete-time discrete-frequency distribution (GDTDFD) is defined as:

$$\hat{D}(l,\theta:\hat{\Phi}) = \sum_{n=-\infty}^{\infty} R_l(n)e^{-j2n\theta} \tag{13}$$

where,

$$R_l(n) = \sum_{m=-\infty}^{\infty} f(l+m+n)f^*(l+m-n)\hat{\Phi}(m,2n) \tag{14}$$

In practice, only a finite time span of the signal is available. This can be represented by applying a sliding window to the signal under analysis, so that equations (13) and (14) can be rewritten as follows:

$$\hat{D}(l,\theta:\hat{\Phi}) = \sum_{n=-N}^{N} R_l(n)e^{-j2n\theta} \tag{15}$$

and

$$R_l(n) = \sum_{m=-M}^{M} f(l+m+n)f^*(l+m-n)\hat{\Phi}(m,2n) \tag{16}$$

Time-Frequency distributions can be used for detecting the rotor speed of AC machines, for constant or variable conditions on the rotor speed. A disadvantage of the Time-Frequency analysis is the amount of processing power required to detect the rotor speed. Additionally, it should be noted that the present algorithm requires the use of a number of samples occurring after the present time analysis index, represented as l in the previous equation. Figure 7 shows the rotor speed estimation obtained using this method. As can be observed, during startup the method is not reliable, because does not accurate information about the stator current.

3.5 Overall speed estimation system

As metioned before, the real time speed estimation is performed using Eq. (8). To tune the T_r parameter, its real value is calculated at slower rated, with the same Eq. (8), but introducing in this equation an accurate speed value, obtained using the time-frequency technique. It is not convenient to adjust the T_r at startup, due to the poor results of the time-frequency method during this stage.

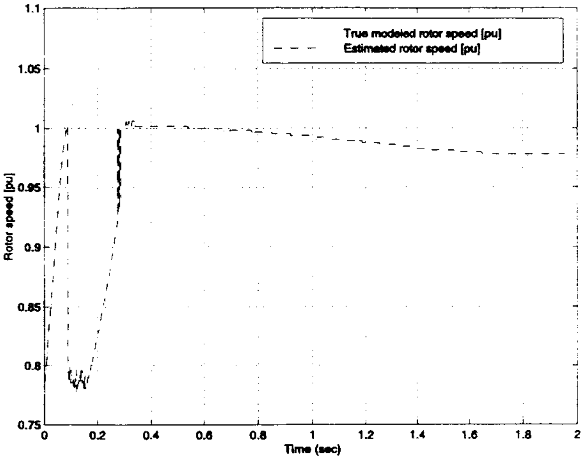


Fig. 7 Time-Frequency speed estimation.

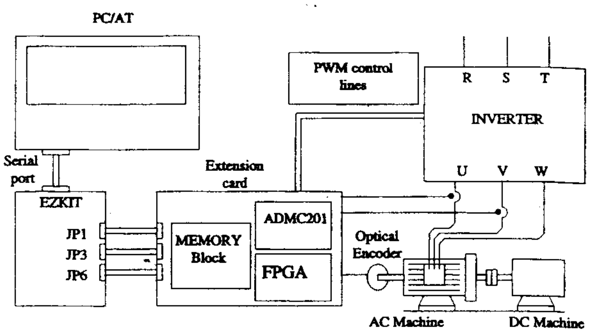


Fig. 8 DSP based test rig.

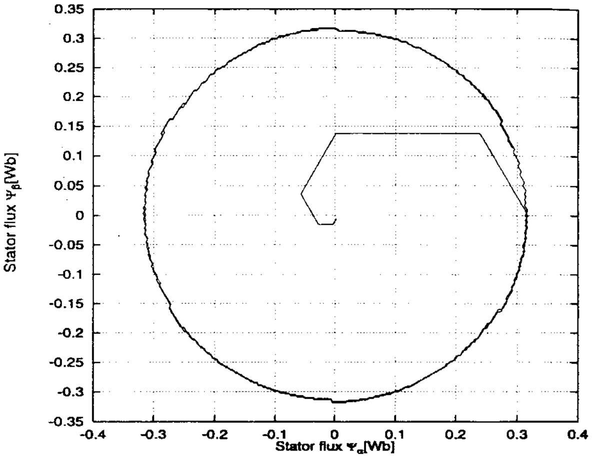


Fig. 9 Stator's flux spatial vector during startup using DTC.

4 EXPERIMENTAL RESULTS

The proposed DTC controller has been numerically simulated using MATLAB 5.3. This model shows the DTC performance controlling the induction machine rotor speed [16]. The speed estimation technique and the rotor time constant adaptation have been tested with this simulation. For the experimental tests a DSP based work bench was used[17]. A diagram of the test rig is shown in Fig. 8. The controlled rectifier bridge uses six 50A and 1200V IGBT's as the switching elements. Fig. 9 shows the stator flux evolution during startup under DTC, with a limited torque requirement, and the corresponding stator current is depicted in Fig. 10.

5 CONCLUSIONS

A useful DTC scheme of the induction machine is proposed and implemented. This controller uses two speed estimation methods, one for dynamic performance, and another for adjusting the rotor time constant. The field-oriented model is used to simplify the speed estimation. A DSP platform has been used to implement this simple and convenient scheme. Experimental results show a

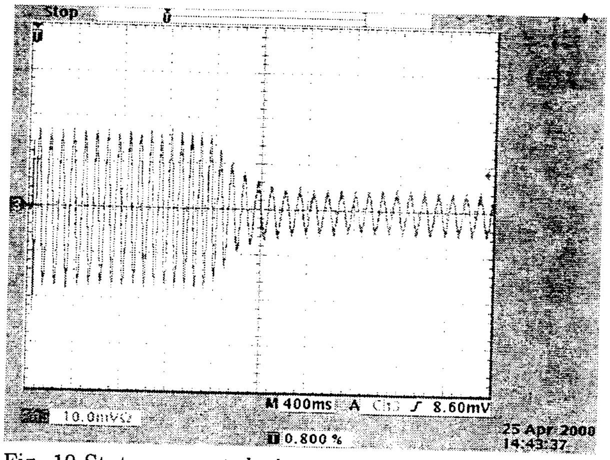


Fig. 10 Stator current during startup using DTC.

good controller performance, in agreement with previous simulation results.

ACKNOWLEDGMENT

The authors want to express their gratitude to CONICIT (S1-97001762) and also to the Dean of Research and Development Bureau of the Simón Bolívar University (GID-04) for the financial support required to perform this work.

REFERENCES

[1] F. Blaschke. "The principle of field orientation as applied to the new TRANSVEKTOR closed-loop control system for rotating-field machines". *Siemens Review*, XXXIX(5):217–220, 1972.

[2] L. J. Garcés. "Parameter adaptation for the speed-controlled static AC drive with a squirrel-cage induction motor". *IEEE Trans. Ind. Appl*, IA–16(2):173–178, March/April 1980.

[3] A. Bellini, A. De Carli, and M. La Cava. "Parameter Identifications for Induction Motor Simulation". *Automatica*, 12:383–386, 1980.

[4] C. Moons and B. Moor. "Parameter Identification of Induction Motor Drives". *Automatica*, 31(8):1137–1147, May/June 1995.

[5] J. Aller and A. Bueno. "On Line Parameter Estimation of the Induction Machine Model using Active and Reactive Power Balance for Spatial Vectors or Field Oriented Drives". In *7th European Conference on Power Electronics and Applications EPE'97*, volume 4, pages 609–614, September 1997.

[6] M. Depenbrock. "Direct Self-Control (DSC) of Inverter-Fed Induction Machine". *IEEE Transactions on Power Electronics*, 3(4):420–429, October 1988.

[7] T. Naguchi and I. Takahashi. "A new quick-response and hight-efficiency control strategy of an induction motor". *IEEE Trans. on Ind. Appl.*, IA–22:820–827, September/October 1986.

[8] J. Nash. "Direct Torque Control, Induction Motor Vector Control Without an Encoder". *IEEE Trans. on Ind. Appl.*, IA–33(2):333–341, March/April 1997.

[9] M. Riese. "Microcontroller Implementation of Speed Sensorless Field Oriented Control of Induction Machine". In *7th European Conference on Power Electronics and Applications EPE'97*, volume 4, pages 476–479, September 1997.

[10] J. R. Cameron, W.T. Thomson, and A.B. Dow. "Vibration and current monitoring for detecting air-gap eccentricity in large induction motors". *IEE proceedings*, 133(3), May 1986.

[11] J. A. Restrepo and P. Bowler. "Analysis of Induction machine slot harmonics in the TF domain". In *Proceedings of the First International Caracas conference on devices, circuits and systems*, pages 127–130. IEEE, December 1995.

[12] José A. Restrepo. "Speed measurement of ac machines using the instantaneous power spectrum (ips)". In *Seventh International Conference on Signal Processing Applications and Technology*, October 1996.

[13] J. Restrepo, M. Gimnez, V. Guzmn, J. Aller, and A. Bueno. "Kernel selection for sensorless speed measurement of ac machines (wigner vs page representation)". In *Proceedings of the 24th Annual Conference of the IEEE Industrial Electronics Society*, volume 2, pages 991–996, August 1998.

[14] B. W. Williams, J. K. Goodfellow, and T. C. Green. " 'Sensorless' speed measurement of inverter driven squirrel cage induction motors". In *Fourth International Conference on POWER ELECTRONICS and VARIABLE-SPEED DRIVES*, number 324, pages 297–300, The Institution of Electrical Engineers, Savoy Place, London WC2, UK, July 1990. IEE.

[15] L. Cohen. "Generalized phse–space distribution functions". *J. Math. Phys.*, 7:781–786, 1966.

[16] J. Aller, J. A. Restrepo, A. Bueno, T. Pagá, V. M. Guzmán, and M. I. Giménez. "Sensorless speed control of the induction machine combining field oriented method and DTC". In *2000 Third International carcas Conference on Devices, Circuits and Systems*, pages 79.1–79.6, April 2000.

[17] J. Restrepo, A. Cabello, J. M. Aller, M. I. Gimnez, V. Guzmn, and A. Bueno. "A dsp system for generic power control applications". In *Proceedings of the 34th Universities Power Engineering Conference*, volume 2, pages 612–615, September 1999.