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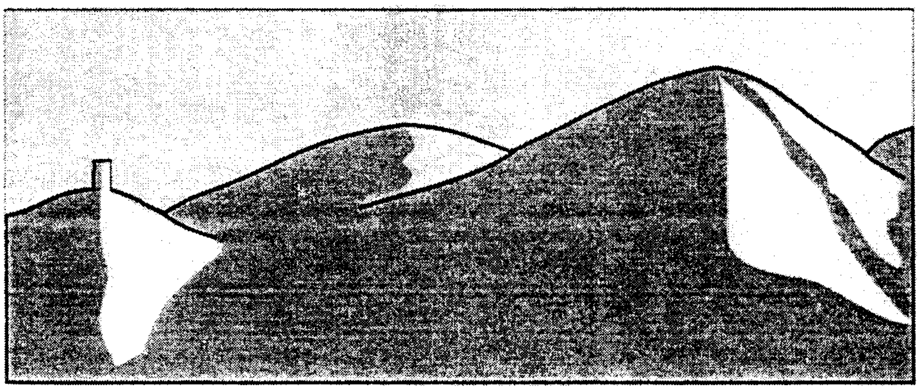

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SENSORLESS SPEED CONTROL OF THE INDUCTION MACHINE COMBINING FIELD ORIENTED METHOD AND DTC

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Abstract – In this paper, a Direct Torque Control (DTC) scheme for the induction machine is presented. The rotor speed estimation is performed using the oriented field model. Time frequency spectral methods are used for accurate speed estimation, using the stator current information. Combining these estimation techniques, a precise T_r adaptation in real time is achieved. The proposed method reduces parameter dependence of the induction machine model in the controller, and removes the need for speed sensor in the mechanical shaft. The dynamic control performance achieved with this technique is comparable to the one obtained using optical encoders.

I. INTRODUCTION

During the last decade, the control of induction machines using space vectors and oriented field transformations has been thoroughly developed [1]. With this technique, the AC machine speed and position controllers have reproduced the DC machine control behavior. The most important limitation in this control method resides in the transformation dependence upon machine model parameters. Many authors [2,3,4,5] have proposed several estimation strategies and real time parameter adaptation techniques to reduce controllers problems and to increase system dynamic performance. Depenbrock [6] proposed and patented the Direct Self-Control (DSC). This technique considerably reduces the speed controller dependence on the induction machine. parameters. Takahashi and Naguchi [7] proposed the Direct Torque Control (DTC), similar to DSC. The DTC controller is based on an inverter bridge activation table with a bang-bang control strategy that uses hysteresis comparators to compare the stator linkage flux and the instantaneous electric torque with their respective references. DTC improves the induction machine controller dynamic performance and reduces the influence of the parameter variation during the operation [8].

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 electric variables' actual values and the machine model parameters [9]. In this technique, precision is reduced due to parameters variation with temperature or saturation. Other speed estimation methods are based on the spectral analysis of the stator current spatial vector [10]. Current harmonics contain information about the rotor speed, produced by the presence of stator and rotor slots, or by the dynamic and static eccentricities. However, this method can not be applied during dynamic operation because the required processing speed is too high for standard DSP hardware. To solve this problem, the use of the time-frequency transformation in order to determine the mechanical speed during the dynamic operation has been proposed by the authors in a previous work [11]. The speed estimation using spectral methods is completely independent from the machine model parameters.

In this work, sensorless speed detection using state estimators and spectral analysis is achieved. An oriented field model is used to determine 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 reduces rotor speed estimation errors. Joining this speed estimation method with the DTC technique, a high dynamic performance system can be obtained, without mechanical sensors in the mechanical shaft. This DTC system uses the vector control technique at startup to limit the inverter currents. The proposed control scheme and the speed estimation method have been modeled in order to verify the theoretical predictions. An experimental DSP based platform is been developed to check the system dynamic performance. Simulation results are shown to illustrate the control's scheme behavior.

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II. DIRECT TORQUE CONTROL

The 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 integrating the electromotive force in the stator winding:

$$\vec{\lambda}_s = \int_o^t \left(\vec{v}_s - R_s \vec{i}_s\right) dt \qquad (1)$$

where:

$$\vec{x}_s = \sqrt{\tfrac{2}{3}} \begin{bmatrix} 1 & e^{j\frac{2\pi}{3}} & e^{j\frac{4\pi}{3}} \end{bmatrix} \cdot \begin{bmatrix} x_{as}(t) & x_{bs}(t) & x_{cs}(t) \end{bmatrix}^T$$

$$\forall x \in \{v, i, \lambda\}$$

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

$$T_e = \vec{\lambda}_s \times \vec{i}_s = \left(L_s \vec{i}_s + L_{sr} \vec{i}_r^{\,s}\right) \times \vec{i}_s = L_{sr} \vec{i}_r^{\,s} \times \vec{i}_s \qquad (2)$$

where:

$$\vec{i}_r^{\,s} = \vec{i}_r \cdot e^{j\theta}$$

The only machine parameter involved in this estimation is the stator resistance R_s. Errors introduced by this parameter variations due to the temperature are very small and can be reduced using real time parametric estimation.

An inverter bridge can produce only eight different states. Each one of these states defines the voltage space vector applied to the stator windings. Six states produce vectors of constant magnitude and $\pi/3$ in phase lag. The other two states are associated with the null space vector. The eight voltage space vectors as function of the bridge connectivity vector are defined in figure 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 necessary change. When the torque reference is inside the hysteresis band, the null voltage vector produced by the smallest number of bridge commutations is chosen [2].

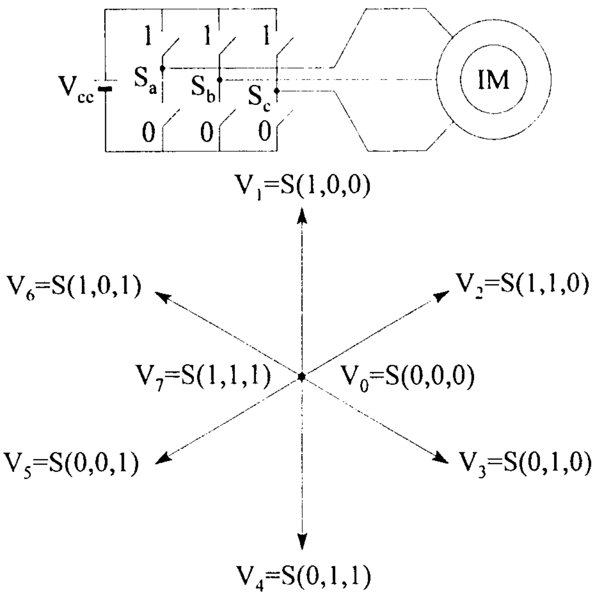

Fig.1 Voltage space vectors as function of the inverter connectivity

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

Using DTC, a 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 in which the linkage flux is positioned, as well as the instantaneous electric torque, the mechanical speed and the linkage flux magnitude.

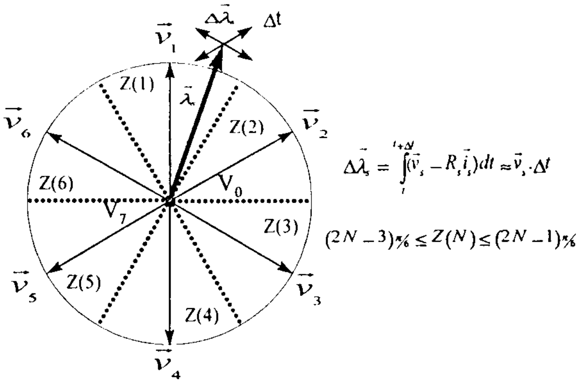

Fig.2 Change of the linkage flux using the voltage space vectors of the stator.

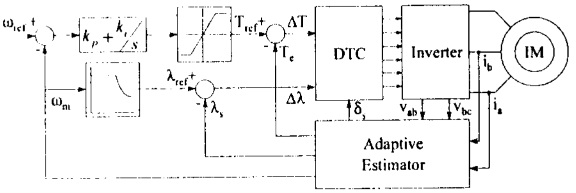

Fig. 3 Speed controller of the induction machine using DTC control and adaptive estimator.

III. ROTOR SPEED ESTIMATION

Estimations are performed in the following areas: Electric torque and linkage flux estimation using external variables, rotor speed estimation using the field oriented model, real time rotor time constant adaptation, speed estimation using time-frequency spectral methods and parametric estimation.

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.

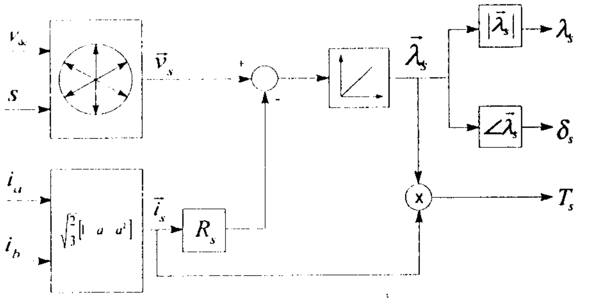

Fig. 4 Electric torque and linkage flux estimator

3.2 Speed Estimation using the Oriented Field Model

Several reference frames can be used to estimate the rotor speed. The oriented field model can perform this task efficiently. Remembering the magnetization current definition:

$$\vec{i}_m \equiv \vec{i}_s + {}^{L_r}\!/_{L_{sr}}\, \vec{i}_r^{\,s} = \vec{i}_s + {}^{L_r}\!/_{L_{sr}}\, \vec{i}_r\, e^{j\theta} \qquad (3)$$

Replacing the rotor current in the stator reference obtained in Eq. 3, $\vec{i}_r^{\,s}$, in the linkage flux expressed as function of stator and rotor currents, the following expression can be written:

$$\vec{\lambda}_s = L_s \vec{i}_s + L_{sr} \vec{i}_r^{\,s} = \hat{L}_s \vec{i}_s + \frac{(L_{sr})^2}{L_r} \vec{i}_m \qquad (4)$$

where:

$$\hat{L}_s \equiv L_s - \frac{(L_{sr})^2}{L_r}$$

From Eq. 4, the magnitude i_m and the spatial position of the magnetization current δ can be calculated, using the flux linkage obtained by Eq. 1. Electric torque in an oriented field model can be expressed as:

$$T_e = \frac{(L_{sr})^2}{L_r} i_m \cdot i_q \qquad (5)$$

From Eq. 5, the quadrature component of the stator current can be obtained, as function of the electric torque, the magnitude of the magnetization current and the machine inductances L_r and L_{sr}. Replacing these results in the quadrature rotor equation, the rotor speed can be obtained as:

$$\dot{\theta} = \omega_m = \dot{\delta} - \frac{L_r}{(L_{sr})^2} \cdot \frac{T_e}{i_m^2} \cdot \frac{1}{T_r} \qquad (6)$$

Figure 5 shows the speed estimator diagram.

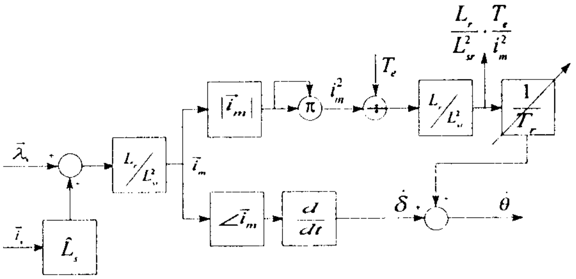

Fig.5 Rotor speed estimation.

3.3 Rotor Time Constant Adaptation

The main error in Eq. 6 is due to temperature-induced variations of the rotor time constant during operation. Inductive parameters are practically constant. In a non-precise speed control, this expression can be used. When the precision requirements are increased, an adaptive estimator is required. To achieve this aim, the rotor slip can used to estimate a more precise value for the rotor time constant T_r. The required slip information can be calculated using the spectral information obtained from the stator spatial current. The time-frequency transformation [10], can be used to perform this calculation during transient operation. The time-frequency algorithm is used only when the machine internal temperature changes the rotor resistance. In any other time, expression 6 is employed in the speed estimation process. Figure 6 shows the rotor time constant adaptation using the spectral slip detector.

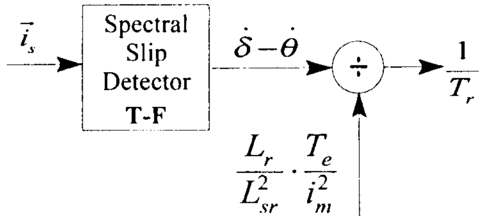

Fig.6 Adaptation of the rotor time constant T_r.

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) [10,11,12], 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.

Signal representation 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:

$$\mathrm{WD}_{f,g}(t,\omega)=\int_{-\infty}^{\infty} f(t+\frac{\tau}{2})\cdot g^*(t+\frac{\tau}{2})\,e^{-j\omega\tau}d\tau \qquad (7)$$

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

$$D(t,\omega;\Phi)=\frac{1}{2\pi}\iiint e^{j(\xi\mu-\tau\omega-\xi t)}\phi(\xi,\tau)f(t+\frac{\tau}{2}).f^*(t-\frac{\tau}{2})d\mu d\tau d\xi \qquad (8)$$

where f(μ) is the time signal, f*(μ) is its complex conjugate, and Φ(ξ,τ) is the kernel of the transformation. A problem with the WD is the appearance of interference terms or cross-terms. Different TF distributions have been proposed which try to address the problem of reducing the magnitude of the interference terms, 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, υ=ξ-t, and integrating over ξ, Eq. 8 can be rewritten as:

$$D(t,\omega;\Phi)=\frac{1}{2\pi}\iint\Phi(\upsilon,\tau)f(\upsilon+t+\frac{\tau}{2})f^*(\upsilon+t+\frac{\tau}{2})e^{-j\omega\tau}d\upsilon d\tau \qquad (9)$$

Where Φ(υ,τ) 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:

$$D(l,\theta;\Phi)=\sum_{-\infty}^{\infty}R_l(n)e^{-j2n\theta} \qquad (10)$$

where,

$$R_l(n)=\sum_{m=-}^{\infty}f(l+m+n)f^*(l+m+n)\hat{\Phi}(m,2n) \qquad (11)$$

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 Eq. 10 and Eq. 11 can be rewritten as follows:

$$D(l,\theta;\Phi)=\sum_{n=-N}^{+N}R_l(n)e^{-j2n\theta} \qquad (12)$$

and

$$R_l(n)=\sum_{m=-M}^{+M}f(l+m+n)f^*(l+m-n)\Phi(m,2n) \qquad (13)$$

The use of Time-Frequency distributions has proved suitable 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 in the future. Figure 7 shows the rotor speed estimation obtained using this method.

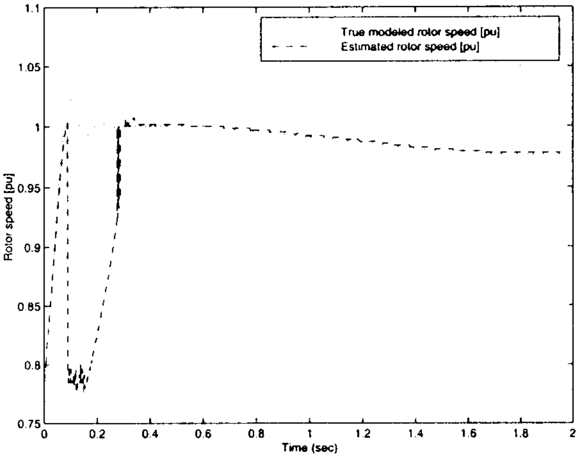

Fig. 7 Time-Frequency speed estimation

3.5 Parameter Estimation

Using parametric estimation, errors introduced by parameter variations can be reduced. Several methods have been proposed in the literature [2,3,4]. Some estimation techniques can be applied in real time. In this work, an active and reactive power estimation is used [5]. This method is precise and fast. Derivative information of the state variables is not required, and the relation between electric power functions and the model parameters is linear. This estimation method minimizes the quadratic error function.

IV. SIMULATION

The proposed DTC controller has been numerically simulated using MATLAB 5.2. This model shows the DTC performance controlling the induction machine rotor speed. The speed estimation technique and the rotor time constant adaptation have been tested with this simulation. Figure 8 shows the electric torque and rotor speed response to a step in the reference signal. Figure 9 shows the stator current spatial vector. A problem during start up is the high current needed to adjust the electric torque. In the field oriented method, the stator current is controlled by the inverter references, but in the DTC, the variable which controls the inverter is the error between the electric torque and its reference. Figure 10 shows the stator current when a different strategy is implemented during the start up period. Initially, a field-oriented control has been used, applying constant direct and quadrature reference of the stator current. Magnetization current, in magnitude and angle, is evaluated using information obtained from DTC and the inductances of the induction machine model. When the stator linkage flux reach 80% of it nominal value, the controller switches from the open loop field-oriented controller to DTC. A significant reduction in stator current is obtained during start up using this strategy.

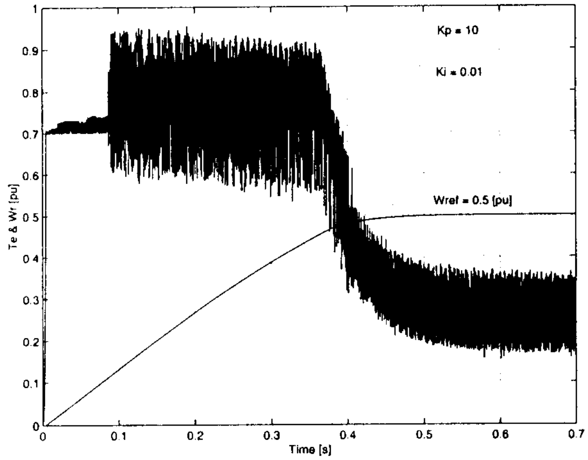

Fig. 8 Electric torque and angular speed response to a reference steep using DTC. Simulation results.

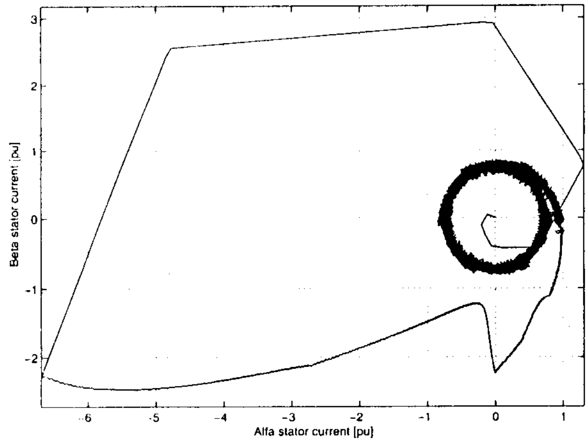

Fig. 9 Spatial vector of the stator current using only DTC strategy. Simulation results.

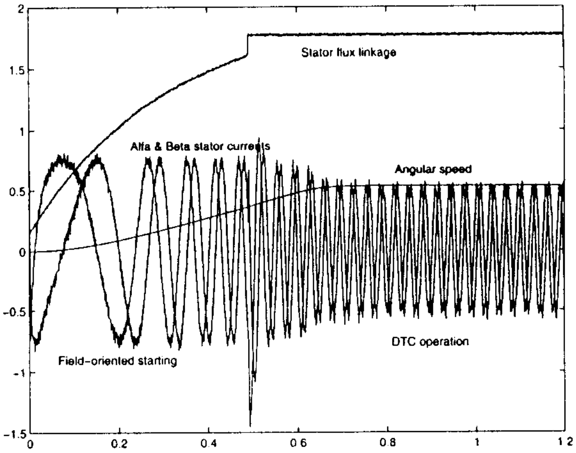

Fig. 10 Stator current using DTC with field-oriented starting strategy. Simulation results.

V. CONCLUSIONS

A useful DTC scheme of the induction machine is proposed. This controller uses two speed estimation methods, one for dynamic performance, and another to adjust the rotor time constant. The field-oriented model is used in order to simplify the speed estimation. An important reduction in stator currents is achieved when a field-oriented strategy is implemented during the starting process. DSP technology can be used to implement this simple and convenient scheme. Simulation results show a good controller performance. A versatile platform is under construction to perform the experimental implementation and validation of the proposed control scheme and will be presented in another publication.

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