DSP IMPLEMENTATION OF A TORQUE METER FOR INDUCTION MOTORS

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***Abstract* – This work describes the steps to implement a torque meter for three phase induction motors based on measurement of stator voltages and currents. The strategy uses the stator flux synthesis through Programmable Cascaded Low-Pass Filters (PCLPF). The electromagnetic torque estimation is done by a DSP microprocessor in real time. The PCLPF filter outlines the problem of necessary numeric integration to calculate the stator flux. The Programmable Cascaded Low-Pass Filter is implemented using Recurrent Neural Network trained by Kalman filter. The DSP based implementation of a torque meter has the same precision comparing with torque meters based on torsion of metallic axes with known elastic constant and strain gauges.**

KEYWORDS

DSP application, torque estimation, Kalman filter, programmable cascade low-pass filter, recurrent neural network.

NOMENCLATURE

Ψ_{ds}^{s} e Ψ_{qs}^{s}	Stator flux components.
v_{ds}^{s} e v_{qs}^{s}	Stator voltage components.
i_{ds}^{s} e i_{qs}^{s}	Stator current components.
R_s	Stator resistance.
$\hat{\Psi}_s$	Total stator flux.
θ_e	Electric angle.
i_{ds} e i_{qs}	Stator current components.
Ψ_{ds} e Ψ_{qs}	Stator flux component.
T_e	Electromagnetic torque.

I. INTRODUCTION

The knowledge of the Three Phases Induction Motor electromagnetic torque is important for Vector Control implementation, electric machines laboratories, specification of drivers, electric pumps, elevators, etc. Nowadays the torque meters, besides high cost, aren't versatile to be easily used directly on machines working in industrials environments once that optical torque meters or strain gauges based, require mechanical connection. In order to solve this problem, this work develops a methodology to implement an electromagnetic torque meter for three phase induction motors. The proposed equipment can be used in industrial and educational environment.

The strategy used to estimate the torque is based on synthesis of the induction motor stator flux, through the integration of the voltage discounted the stator resistance drop [1]. The problem, very known in the literature, is the offset D.C. presented by numeric integration. This difficulty is outlined through a Programmable Cascade Low-Pass Filter (PCLPF) implemented with Recurrent Neural Networks. DSP56002 of Motorola operating at 40 MHz executes the torque estimation calculations. Hall effect sensors measure the voltage and current signals. The signals are digitized through Texas Instruments ADS7864, analog to digital converter (A/D), with 12 bits and conversion rate of 8kHz.

The equipment has a smaller cost and compatible precision when compared with the equipments using torsion of metallic axes and strain gauges. Those are expensive and limited application range.

Another advantage of the torque estimation process, compared with traditional equipments, it is the possibility to show the dynamics of induction motors electromagnetic torque. Differently of the traditional equipment that just has reliable results on stead state.

The only induction motor parameter necessary to this implementation is the stator resistance. This resistance, once measure, can be compensated easily for temperature variations, once that the stator resistance varies linearly with the stator temperature. Several thermistors can be mounted in different locations of the stator winding and the compensated resistance can be estimated [7].

The developed equipment presents a good reliability, wider ranges of power and industrial environment direct application.

II. STRATEGY

1)Synthesis of the Stator Flux

The synthesis of stator flux, technique also used on the Stator Flux Oriented Vector Control [2], calculates the stator fluxes vectors on stationary reference frame Ψ_{ds}^{s} and Ψ_{qs}^{s}, through the stator voltage integration (V_{ds}^{s} , V_{qs}^{s}), removed the voltage drop ($R_s i_{ds}^{s}$, $R_s i_{qs}^{s}$) across the stator resistance.

The voltages (V_{ds}^{s} , V_{qs}^{s}) and the currents (i_{ds}^{s} , i_{qs}^{s}), are calculated through the Clark transformation, also denominated *3Φ/dq0* transformation, generating stationary reference frame values.

The stator fluxes Ψ_{ds}^{s} and Ψ_{qs}^{s} are calculated by the integral of these differences by the equations [1]:

$$\Psi_{ds}^{s} = \int (v_{ds}^{s} - i_{ds}^{s} R_s)dt \quad \text{[Wb]} \tag{1}$$

$$\Psi_{qs}^{s} = \int (v_{qs}^{s} - i_{qs}^{s} R_s)dt \quad \text{[Wb]} \tag{2}$$

Once calculated the flux on the axes d and q is possible to calculate the total stator flux:

$$\hat{\Psi}_s = \sqrt{(\Psi_{ds}^{s})^2 + (\Psi_{qs}^{s})^2} \quad \text{[Wb]} \tag{3}$$

To obtain the electromagnetic torque developed by the machine, the synchronous reference frame model is used. To do that, it is necessary the calculation of the sines and cosines of the electric angle θ_e of the circulating vector on rated frequency at machine terminals. These equations are given by:

$$\operatorname{sen}\theta_e = \frac{\Psi_{qs}^{s}}{\hat{\Psi}_s} \tag{4}$$

$$\cos\theta_e = \frac{\Psi_{ds}^{s}}{\hat{\Psi}_s} \tag{5}$$

also,

$$\theta_e = \operatorname{sen}^{-1}\left(\frac{\Psi_{qs}^{s}}{\hat{\Psi}_s}\right) \quad \text{[rad]} \tag{6}$$

Now, it is possible to determine the stator currents i_{ds} and i_{qs} and also the stator fluxes Ψ_{ds} and Ψ_{qs} using the equations:

$$i_{ds} = i_{qs}^{s}\cos\theta_e - i_{ds}^{s}\operatorname{sen}\theta_e \quad \text{[A]} \tag{7}$$

$$i_{qs} = i_{qs}^{s}\operatorname{sen}\theta_e + i_{ds}^{s}\cos\theta_e \quad \text{[A]} \tag{8}$$

$$\Psi_{ds} = \Psi_{qs}^{s}\cos\theta_e - \Psi_{ds}^{s}\operatorname{sen}\theta_e \quad \text{[Wb]} \tag{9}$$

$$\Psi_{qs} = \Psi_{qs}^{s}\operatorname{sen}\theta_e + \Psi_{ds}^{s}\cos\theta_e \quad \text{[Wb]} \tag{10}$$

Multiplying the stator flux for the stator current, represented on synchronous reference frame, the machine electromagnetic torque can be calculated using the following equation:

$$T_e = \frac{3P}{4}\left[\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}\right] \quad \text{[Nm]} \tag{11}$$

The Fig.1 illustrates the simplified block diagram of the torque meter.

2)Programmable Cascade Low-Pass Filter (PCLPF)

The numeric integration, necessary to calculate the synthesis of stator flux (equations 1 and 2), presents a DC offset problem, mainly in low frequencies. Bose and al. [2] proposed a solution for this problem using a Programmable Low-Pass Filters in Cascade. The Fig.2 shows the implementation of such filter using two stages. The parameters such time constant (τ) and gain compensation (G) are settled as function of the frequency (ω_e), by the equations (12) and (13).

$$\tau = (1/\omega_e)\, tg[(1/n)[tg^{-1}(\tau_h\, \omega_e) + 90^0]] = f(.)\omega_e \text{ [s]} \tag{12}$$

$$G = (1/\omega_e)\sqrt{[1+(\tau\,\omega_e)^2]^n\,[1+(\tau_h\,\omega_e)^2]} = g(.)\omega_e \tag{13}$$

Where:

ω_e	60Hz (frequency used in the tests).
n	Number of filter stages.
f(.) e G(.)	Filter time constant and gain compensations
τ_h	Time constant of the hardware analog low-pass filter

It is important to notice that τ keeps the phase displacement of each stage identical for any chosen frequency and G guarantees that the gain of the PCLPF produces the ideal gain to get the integration effect. The time constant τ_h compensates the phase displacement of a possible analog filter that could be inserted in the measurement system in case of the motor being fed by inverters.

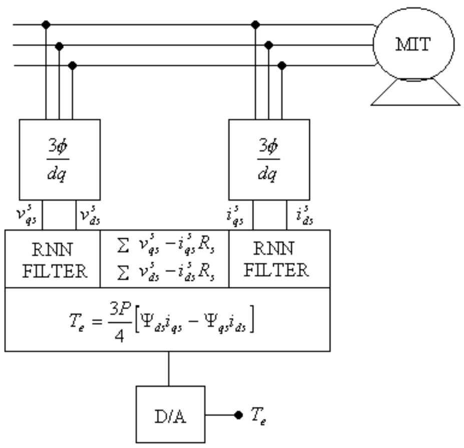

Figure 1 – Simplified Diagram of the Equipment

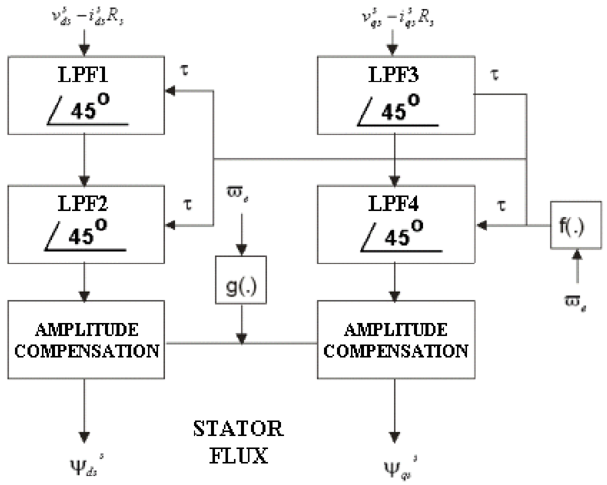

Figure 2 – Programmable Cascaded Low-Pass Filter (PCLPF)

3)Neural Network PCLPF Implementation

The PCLPF implementation was done through Recurrent Neural Network trained by Kalman Filter [3]. This RNN-PCLPF implementation presents the same stead state behavior of traditional PCLPF, but better transient response under frequency and amplitude variation [4].

The Recurrent Neural Networks uses unitary delays (Z^{-1}) to represent the Programmable Cascade Low-Pass Filter dynamics. The Fig.3 illustrates the RNN architecture used in place of traditional PCLPF. The weights values W_{ij} are calculated off-line for each specific frequency. The RNN internal activity is represented by neuron equations, on discrete time k, described by equations 14 and 15.

$$\Psi_{ds}^s(k) = \sum W_{ji}(k)[V_{ds}^s - R_s i_{ds}^s] \qquad (14)$$

$$\Psi_{ds}^s(k) = \sum W_{ji}(k)[V_{ds}^s - R_s i_{ds}^s] \qquad (15)$$

Where Ψ_{ds}^s and Ψ_{qs}^s are the estimated fluxes, V_{ds}^s and V_{qs}^s are the stator voltages and $R_s i_{ds}^s$ and $R_s i_{qs}^s$ are the voltage drop across the stator resistance.

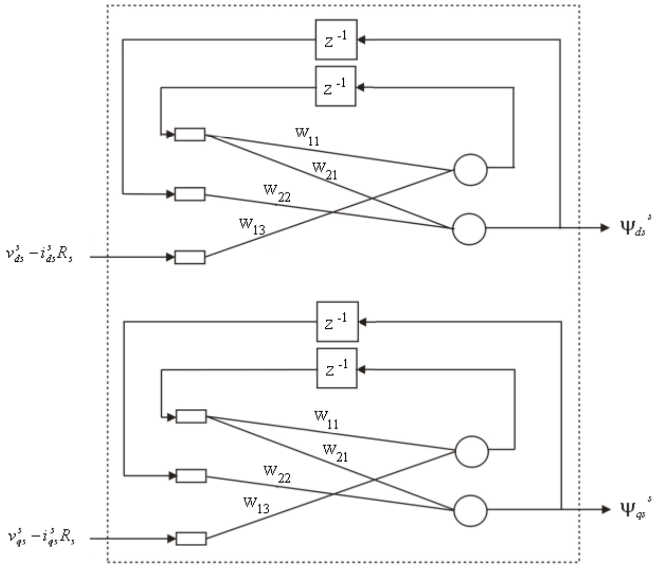

Figure 3 – Recurrent Neural Network

The simulation of flux synthesis, through the filter PCLPF implemented with RNN, denominated PCLPF-RNN, presents an error around 10^{-3} [5]. This error in the simulations, for 80 (Nm) torque, was found to be smaller than 0.1%, perfectly acceptable for an useful torque meter.

III. TORQUE ESTIMATION SIMULATION

The simulation program MATLAB/SIMULINK was used to simulate the developed strategy. The Fig.4 shows the simulation results when a variable load torque is applied to an Induction Motor. It can be observed thatelectromagnetic torque generated by the machine coincides with estimated torque.

TABLE 1
Parameters of the Simulated Induction Motor

Rotor Resistance–Rr	0,4165 Ω
Stator Resistance–Rs	0,5814 Ω
Stator Inductance–Lls	3,479 mH
Rotor Inductance–Llr	4,15 mH
Inductance of Magneticize–Lm	78,25 mH
Frequency	60 Hz
Number of Poles	4
Moment of Inertia	0,1 kg m^2

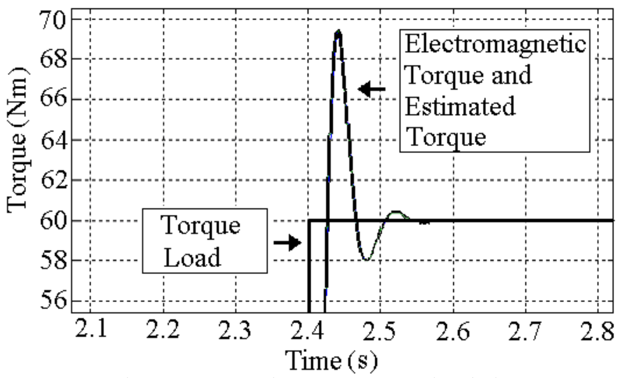

Figure 4 – Transient Torque on Simulation

IV. THE TORQUE METER PROTOTYPE

The Fig.5 illustrates the block diagram of the developed torque meter. The system is composed of voltage and current sensors, data acquisition board with A/D converters, DSP Microprocessor, D/A converter and PC interface. The system uses Hall effect sensors for voltage and current, ADS7864 Texas Instruments A/D converter and Motorola DSP56002 microprocessor. The data acquisition board developed around the circuit ADS7864 uses a 12 bits A/D converter running at 8kHz, with six input channels sampled simultaneously. The DSP Microprocessor board DSP56002, responsible for all calculations, runs at 40MHz.

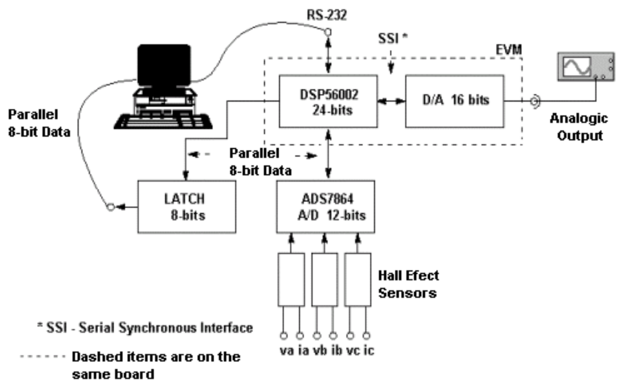

Figure 5 – Block Diagram of the System

1)Data Acquisition Board with ADS7864

The data acquisition board was built using the integrated circuit ADS7864 of Texas Instruments, an analog to digital converter with frequency up to 500kHz, with six input channels. The Fig.6 illustrates the block diagram of the ADS7864.

The Fig.7 presents the picture of the data acquisition board developed for the project. On this board there are the signal conditioning circuits for the Hall effect sensors. The voltage and current Hall sensors were mounted on board independent from the DSP board to facilitate the use close to the machine under test.

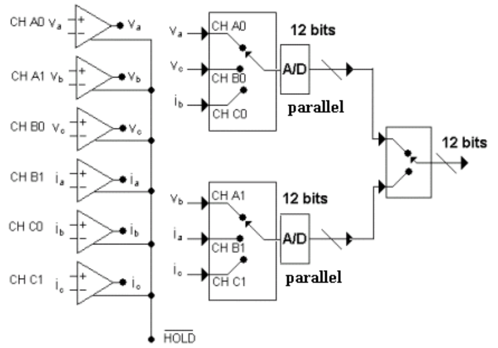

Figure 6 – Six Channels Analog to Digital Converter

2)Microprocessor DSP56002 Board

The Fig.8 illustrates the block diagram of the data acquisition board connected to DSP Microprocessor board.

The Motorola DSP56002 board is connected to a PC by serial port with transfer rate of 19200 bps [6]. The program was developed in assembly language. The Fig.9 presents the picture of the complete system during the test.

An interruption is generated each 125µs giving a sampling frequency of 8kHz. Each 125µs the DSP collect from the ADS7864 six samples of voltage and current (Va, Vb, Vc, Ia, Ib, Ic).

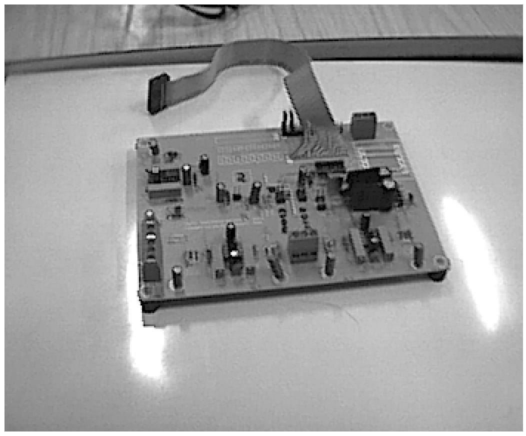
Figure 7 – Picture of the Data Acquisition Board

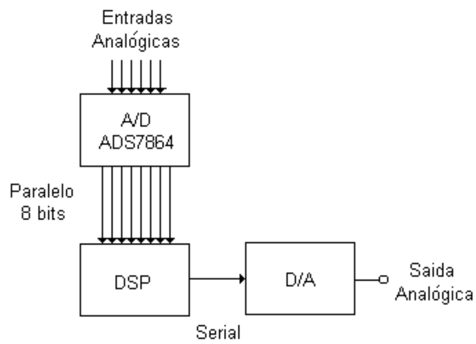

Figure 8 – Block Diagram of Data Acquisition Board

After receive the signals from A/D, the DSP executes the calculus to do the conversion 3Φ/dq0, the synthesis of the stator flux through PCLPF-RNN filter and finally calculates the electromagnetic torque. After that it return waiting a new interruption from the timer.

Finally the electromagnetic torque value is placed in a latched where a routine, written in DELPHI on PC, shows the value on the monitor.

V. TESTS AND RESULTS

To validate the torque estimation, these values were compared with the values obtained from the commercial torque meter Monitek, based on torsion of metallic axes and strain gauges placed appropriately along the axis.

The Fig.10 displays the sensor of the equipment Monitek installed between induction motor and the D.C. generator

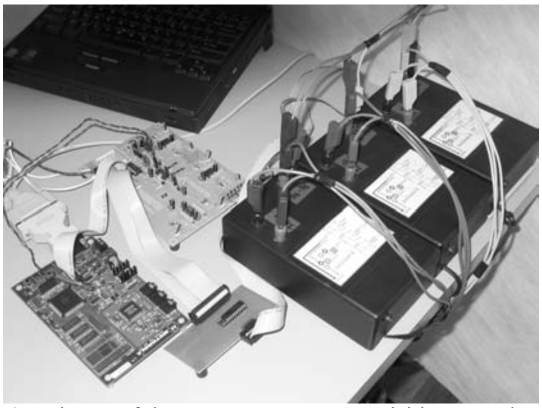

Fig.9 – Picture of the Prototype: Data Acquisition Board, DSP Board and Boxes for Hall Sensors

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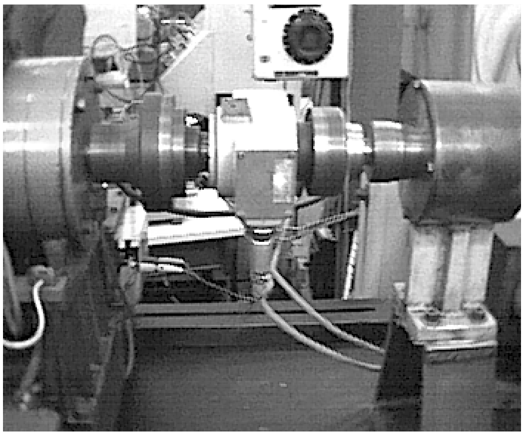

Figure 10 – Sensor of Monitek Between D.C. Machine and Induction Motor

During the tests an induction motor is coupled to a D.C. generator working as a load. The load torque changing is obtained varying a liquid resistance plugged to the D.C. generator.

The three phases induction motor parameter used in the tests are showed in the Table 2.

TABLE 2
Data of the Induction Motor Used on the Tests

Manufactory	EBERLE
Nominal voltage	220 V
Connection	Triangle
Rotation	1765 R.P.M.
Nominal current	26 A
Model	B132 S 4 / ESP
FS	1.0
Ip/In	8,6
Nominal power	10 CV
Isolation	B
Category	H
Stator resistance	0,477 Ω

The Fig.11.a shows the estimated torque obtained by the torque meter under load variations. The Fig.11.b displays the transient response for a sudden load changing.
The results obtained in the tests were compared, for validation purpose, with the values obtained with the torque meter Monitek. Table 2 shows these values.

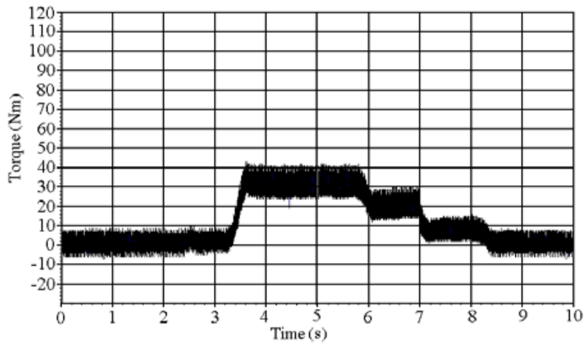

Figure 11.a – Estimated Torque Under Load Variation Variation

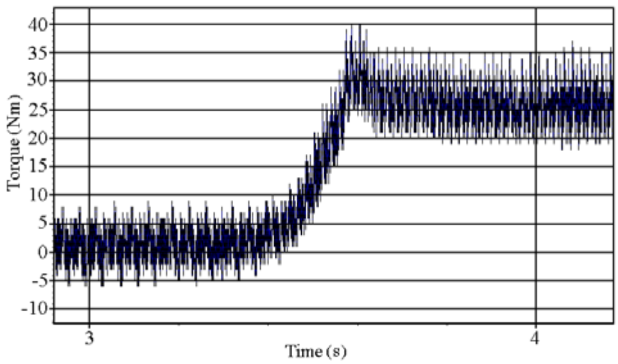

Figure 11.b – Estimated Torque on Transient Load Variation

TABLE 3
Torque Values: From the Estimator and the Torque Meter Monitek

Monitek [Nm]	Estimator [Nm]	Current [A]
11,55	11,75	15,04
19,12	18,75	17,25
23,45	23,8	19,02
28,52	28,6	21,24
32,45	32,5	23,1

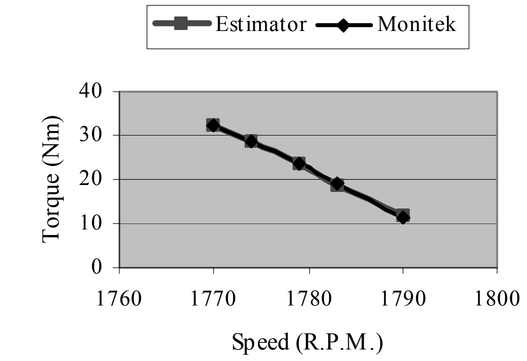

Figure 12 – Estimated and Measured Torque versus Speed

The Fig.12 displays the curves of the torque obtained by the DSP based equipment and the commercial equipment Monitek. The curves are torque versus motor speed.

The error between the estimated and measured torque can be observed in Fig.13. The maximum error is smaller than 2%.

For the Fig.13 the equation was used:

$$Error\% = \left| \frac{Torque\,Measured - Torque\,Estimated}{Torque\,Measured} \right| * 100\%$$

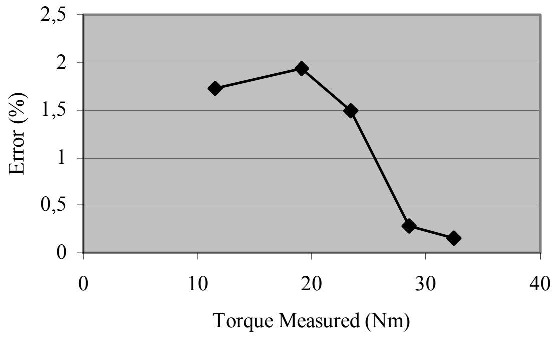

Figure 13 – Estimated Torque Error Versus Measured Torque

VI. CONCLUSIONS

The development of an induction motor torque meter using DSP based in the synthesis of the stator flux has been described. The use of PCLPF filters built with RNN and implemented on DSP shows reliable when the results were compared with those obtained from an equipment very known of the research laboratories.

The DSP turns realizable the estimation process in real time. The DSP56002, operating in 40MHz, takes 68μs to execute all the calculations and to produce an estimate for the torque.

The stator resistance variation with the temperature didn't influence the estimation process, that because there was not temperature variation during the tests. If it is so, compensation is possible and simple to be implemented [5].

The comparison among the measured and estimated values of the torque shows that, for the tested motor, the error was smaller than 2%.

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