DIRECT TORQUE CONTROL WITH STATOR RIPPLE FREQUENCY IMPOSED BY DITHERING

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***Abstract* – Direct Torque Control of induction motors is the latest step in motor drives. Hysteresis band amplitude choice is one of the initial difficulties involved in the technique since it determines ripple frequencies and amplitude error of control variables. Correlation between hysteresis bands, ripple frequencies and error amplitudes is due to the establishment of limit cycles in inner control loops. In this paper, an alternative structure which simplifies designers work through the control of flux and torque error amplitudes by means of dithering is presented. A simulation environment developed in MATLAB/ Simulink is used to obtain the results. This environment takes into account the dynamic behavior of each individual block allowing for the project and test of controlling structures for DTC in an inexpensive way.**

KEYWORDS

Direct torque control, induction motors, motor drives.

I. INTRODUCTION

Direct Torque Control – DTC started to be developed in the 80´s, due to works of Takahashi and Noguchi (1985) and Depenbrock (1988) applying field orientation and spatial modulation principles.

As a main feature, DTC presents a quick torque response and an excellent speed regulation in the speed control loop, proving to be an adequate alternative to transportation systems such as motor drives in electric vehicles, where it substitutes the former scalar control with improved performance (Faiz et al., 1999).

Classical DTC strategy uses two and three-level hysteresis comparators to perform a comparison between stator flux and electrical torque with their references. This strategy is characterized by the presence of ripple oscillations in the stator flux and torque control loops as a drawback. Frequency and amplitude of these ripple oscillations appear as consequences of applied hysteresis band amplitudes. Hence, hysteresis band amplitude choices are presented as an initial problem for designers, since they are associated with ripple oscillation frequencies and precision of imposed references.

In this paper, the effect of hysteresis band amplitudes on ripple oscillation frequencies in a traditional DTC drive was studied. Later on, an alternative strategy which allows for the design of frequency and amplitude of ripple oscillations was proposed. Designers work is simplified through the direct definition of amplitude errors to be expected on the control variables.

Results where obtained by the use of a simulation environment developed by Ferreira and Haffner (2000) using MATLAB/ SIMULINK. This environment takes into account the dynamic behavior of each individual block allowing for project and test of DTC controlling structures in an inexpensive way

II. TRADITIONAL DTC

DTC philosophy is based on hysteresis control of torque and stator flux, implemented with two independent control loops, Fig. 1. In the torque control loop, a direct comparison between reference and estimated torque is performed, allowing for very fast torque response though with increased switching frequency applied to the inverter. In each calculation cycle, hysteresis controller results are processed together with stator flux position to generate a new command for the inverter. A motor model is used to estimate stator voltage, stator flux and torque using the information obtained from the current sensors and DC link sensor.

Since both control loops are implemented with hysteresis comparators, limit-cycle ripple oscillations are observed in flux and torque loops. They appear mainly as consequence of hysteresis band amplitudes, but also of switching strategies, mechanical speed and sampling period.

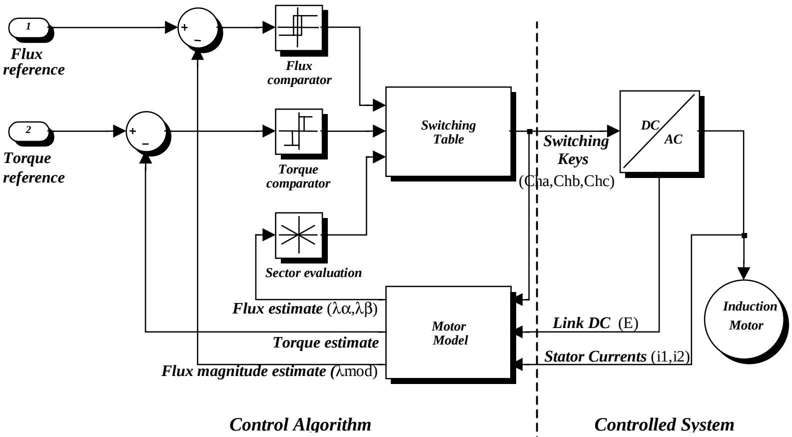

Fig. 1. Traditional DTC Strategy

Fig. 2 and Fig. 3 show ripple oscillation frequency dependence on hysteresis band amplitudes. Results were obtained using the motor parameters listed in the APPENDIX.

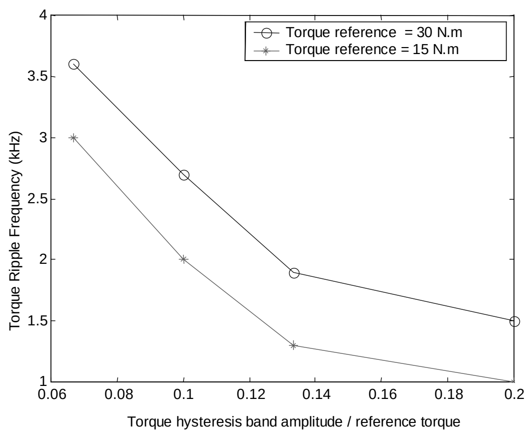

Fig. 2. Relation between amplitude of torque hysteresis band and ripple frequency - DTC without Speed Control.

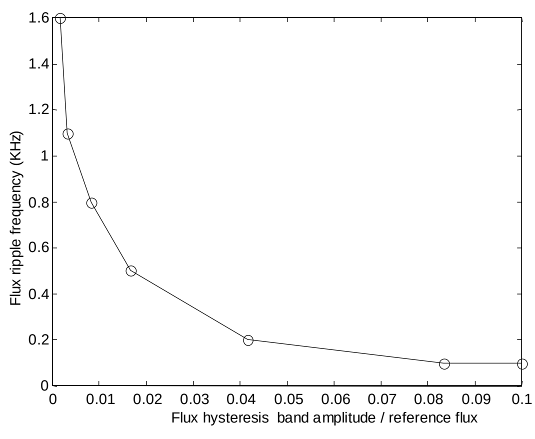

Fig. 3. Influence of flux hysteresis band on ripple oscillation frequency - DTC without Speed Control.

III. DTC WITH RIPPLE FREQUENCY FORCED BY DITHERING

Two different topologies where tested for the imposition of ripple frequencies. The first strategy establishes ripple oscillations simultaneously on the flux and torque control loops while the second acts only on the flux loop.

Both topologies use relay comparators without hysteresis, reducing the problem of limit-cycle oscillations. In this case, the limit-cycle oscillations are due to the delay between acquisition and processing of measured signals.

Sinusoidal signals are superposed to reference errors before relay comparators introducing oscillations similar to limit-cycle oscillations and stabilizing the control loop. The advantage of this alternative is to permit separated amplitude and frequency definitions which are closely related to reference errors and to the switching frequency resulting on the inverter (Fig. 4).

Strategy 1, uses a two-level relay without hysteresis in the torque control loop. This approach does not permit to apply null vectors in four-quadrant operations, which is a drawback considering its increase in inverter switching. On the other hand, operation without null vectors establishes flux faster and is more suitable to near-zero-speed operations (Buja, 1997).

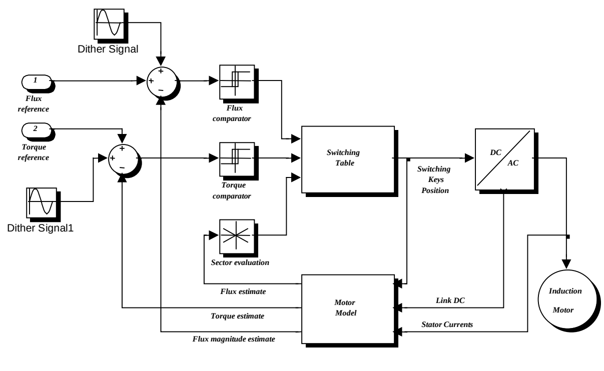

Fig. 4: Frequency Imposition, Strategy 1.

Strategy 2, which implements dithering only in the flux loop, proved to be more adequate. It results in a reduced switching on the inverter by using the same three-level torque comparator presented in the traditional drive (Fig. 1). It allows for null-voltage vectors to be applied in four-quadrant operations.

IV. RESULTS

Through the use of the simulation environment developed in Matlab/Simulink (Fig. 5), testing and validation of new topologies is straightforward. Results were saved in the simulation environment and analyzed offline. The Matlab function PSD (Power Spectral Density Estimate) was used to estimate power spectral density in the frequency analysis of the control loops.

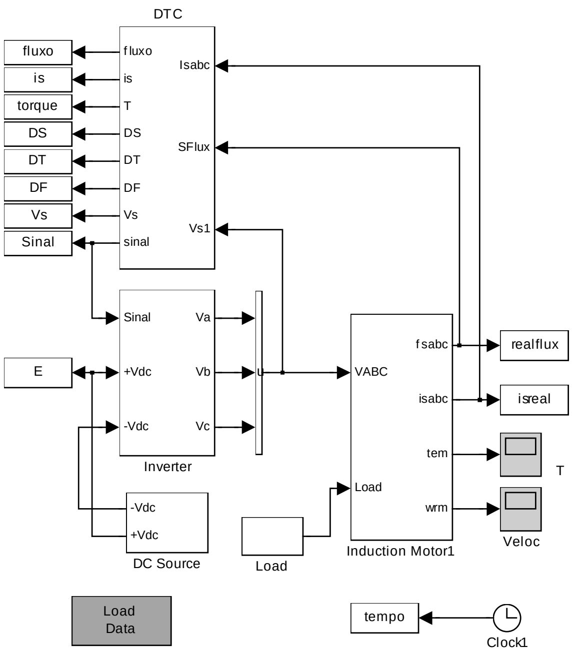

Fig. 5. Simulation environment in Simulink

A. Comparison between strategies

Simulations were held without flux estimation and speed control since the work focus was only comparing different strategies and their influences on ripple frequencies. A torque reference of 30 N.m and a load of 10 N.m were applied to the simulation model. Inverter switches were actualized every 25 μs and therefore simulation time step was fixed to 5 μs.

Frequency analysis was performed through spectral distributions using power spectral density estimation with Hanning window of 4096 points. Fig. 6 refers to the traditional DTC strategy while Fig. 7 and Fig. 8 refer to strategies using dithering. Comparing the alternatives, the effectiveness of ripple imposition is evident.

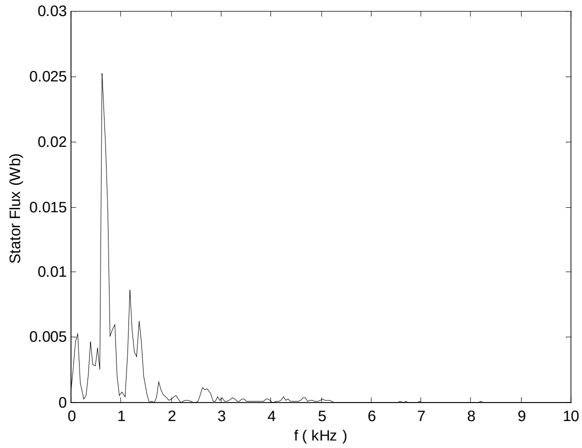

Fig. 6. Stator Flux PSD – Traditional DTC - flux hysteresis band amplitude = 0.01 , torque hysteresis band amplitude = 2.

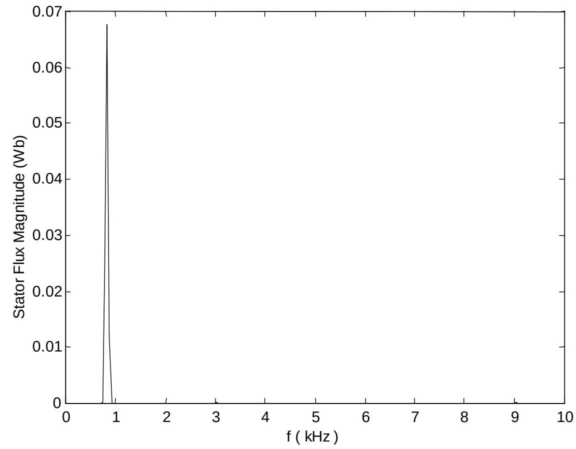

Fig. 7. Stator Flux PSD – Strategy 1 – flux dither frequency (amplitude = 0.01, frequency = 825 Hz) and torque dither frequency (amplitude = 2, frequency = 3.0 KHz).

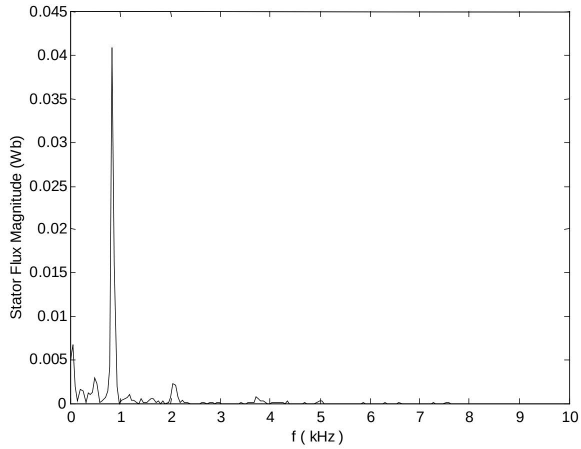

Fig. 8. Stator Flux PSD – Strategy 2 – flux dither frequency (amplitude = 0.01, frequency = 825 Hz) and torque hysteresis band amplitude = 2.

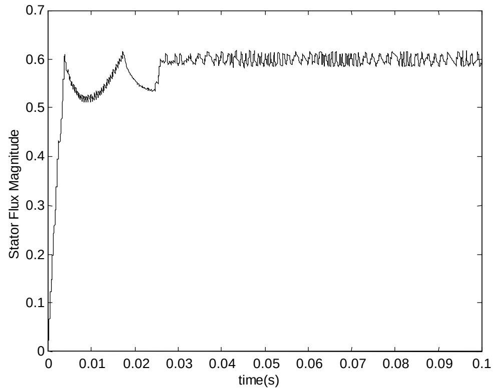

Fig. 9. Stator Flux Magnitude – Traditional DTC – flux hysteresis band = 0.01, torque hysteresis band = 2.

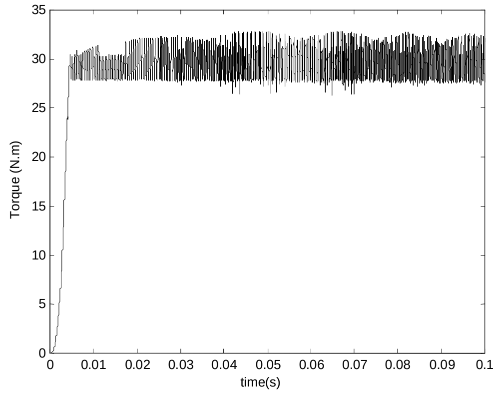

Fig. 10. Torque – Traditional DTC – flux hysteresis band = 0.01, torque hysteresis band = 2.

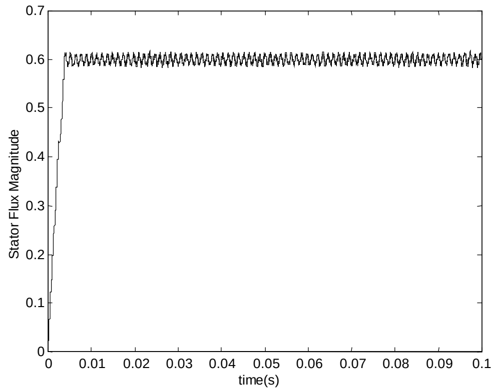

Fig. 11. Stator Flux Magnitude – Strategy 1 – flux dither frequency (amplitude = 0.01, frequency = 825 Hz) and torque dither frequency (amplitude = 2, frequency = 3.0 KHz).

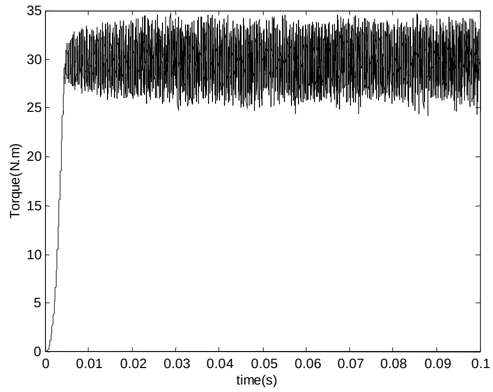

Fig. 12. Torque – Strategy 1 – flux dither frequency (amplitude = 0.01, frequency = 825 Hz) and torque dither frequency (amplitude = 2, frequency = 3.0 KHz).

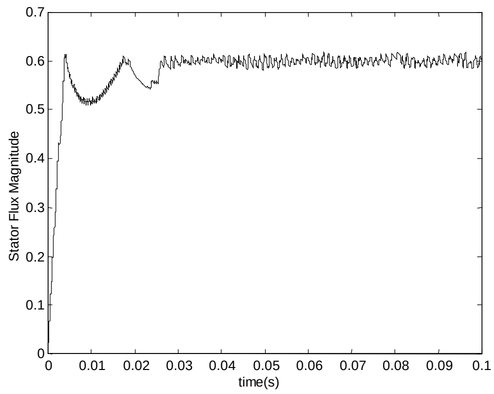

Fig. 13. Stator Flux Magnitude – Strategy 2 – flux dither frequency (amplitude = 0.01, frequency = 825 Hz), torque hysteresis band = 2.

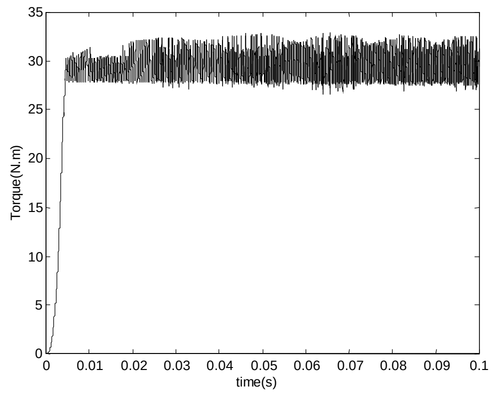

Fig. 14. Torque – Strategy 2 – flux dither frequency (amplitude = 0.01, frequency = 825 Hz), torque hysteresis band = 2.

Fig. 9 to Fig. 13 show torque and flux responses for the studied cases.

Fig.12 shows increased torque ripple which is due to the application of a two-level relay comparator, hence without utilization of null vectors in the control. Flux is established faster in Fig. 11 for the same reason.

B. Comparison through Total Harmonic Distortion

Flux ripple frequency imposition was verified by means of total harmonic distortion estimation. THD function was developed in Matlab according to equation (1).

$$THD = \sqrt{\frac{P_t - P_0}{P_0}} \qquad (1)$$

where P_t stand for power density integrated in the band, from 0 to Nyquist frequency, and P_0 stands for power density integration from F-2 points to F+2 points, with F being the imposed frequency. Both integrations were performed according to trapezoidal rule.

In the simulation performed, flux ripple frequency was forced to 825 Hz.

Analyzing results presented in Table 2, it is clear that frequency is imposed through strategies 1 and 2 with a consequent smaller THD comparing to traditional DTC strategy.

TABLE II
THD Comparison

Strategy	THD
Traditional DTC	3.934
DTC w/ flux and torque ripple imposition	0.4286
DTC w/ flux ripple imposition	0.8971

V. CONCLUSION

Through application of the proposed strategies, it is possible to observe the ripple frequency imposition which avoids coupling between amplitude and frequency of ripple oscillations. Therefore, simplifying design of hysteresis band amplitudes.

Strategy 1 presents a better flux regulation with an increased inverter switching and it is more adequate to machine starting.

APPENDIX

The induction motor parameters used in the simulations are presented in Table I.

TABLE I
Induction motor parameters

Number of poles	4
System inertia	0.062 kg.m
Stator resistance	0.728 Ω
Rotor resistance	0.706 Ω
Stator inductance	0.0996 H
Rotor inductance	0.0996 H
Mutual inductance	0.0969 H

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