A Novel Direct Torque Control Scheme for Induction Machines With Space Vector Modulation

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***Abstract*— In this paper a new method for Direct Torque Control (DTC) based on load angle control is developed. The use of simple equations to obtain the control algorithm makes it easy to understand and implement. Fixed switching frequency and low torque ripple are obtained using space vector modulation. This control strategy overcomes the most important drawbacks of classic DTC.**

Results shows the feasibility of the proposed method, obtaining good speed control bandwidth while overcoming classic DTC drawbacks.

***Index Terms*— Electric Drives, AC Machines, Direct Torque Control, Space Vector Modulation.**

I. Introduction

In recent years much research has been developed in order to find simpler control schemes for induction motors that meet the most demanding requirements, such as low torque ripple, low harmonic distortion or quick dynamic response.

Today Field Oriented Control (FOC) [1] and Direct Torque Control (DTC) [2],[3] are considered the most important techniques to achieve high dynamic performance in AC machines.

The use of current control loops in a rotating reference frame to decouple torque and flux control is the main characteristic of FOC. The use of these controllers adds an additional time delay making torque dynamic response slower. Space vector modulation (SVM) has been frequently used in FOC to generate the gate pulses for the inverter semiconductors.

Classic DTC makes use of hysteresis comparators with torque and stator flux magnitud errors as inputs to decide which stator voltage vector is applied to motor terminals. The complex plane is divided in six sectors, and a switching table is designed to obtain the required vector based on the hysteresis comparators outputs. Due to fast time constants of stator dynamics it is very difficult to keep machine torque between the hysteresis bands. This can be done either by increasing the sampling frequency as in [4], thus increasing switching frequency, commutation losses and computation requirements, or using multilevel power converters [5],[6].

The use of hysteresis comparators in classic DTC implementations give rise to variable switching frequency, which depends on rotor speed, load, sample frequency, etc. This variable switching frequency may excite resonant dynamics in the load and hence constitute a serious drawback of DTC. The use space vector modulation in conjunction with DTC has been proposed as a solution to overcome the above mentioned problems [7]-[17].

In [7],[8] and [9] a second degree equation with parameters depending on machine operating point must be solved to obtain the stator vector reference. In [10] and [11] an inverse machine model is used for stator flux ($\boldsymbol{\psi_s}$) calculation. The use of PI controllers for torque and stator flux in a rotating reference frame is proposed in [12], leading to a control scheme that is similar to field oriented control.

The technique proposed in this paper is similar to that used in [13],[14] for permanent magnet synchronous motors and is not clearly explained in [15], and[16].

The main contribution of this work is to use a new and very simple one step flux control algorithm for induction machine control using DTC and SVM (DTC-SVM) and few controllers, avoiding coordinate rotations and complicated predictive controllers.

Results for the proposed strategy are presented for a 5.5 [kW] induction motor and are compared with FOC and classic DTC in terms of torque transient response, torque ripple and switching frequency. Finally it is concluded that improved results are obtained with a simple algorithm based on an easy to understand theoretical principle.

II. Theoretical Background

Applying the usual space vector transformation to a three phase voltage system, a single space vector is defined by

$$\boldsymbol{v_s} = \frac{3}{2}\left(v_a + a v_b + a^2 v_c\right), \tag{1}$$

where $a = -1/2 + j\sqrt{3}/2$, and v_a, v_b and v_c are stator phase voltages, it is possible to obtain a simple equations set that describe the AC machine dynamic behavior in a stator fixed coordinate system [18]. These equations are:

$$\boldsymbol{v_s} = R_s \boldsymbol{i_s} + \frac{d\boldsymbol{\psi_s}}{dt} \tag{2}$$

$$0 = R_r \boldsymbol{i_r} + \frac{d\boldsymbol{\psi_r}}{dt} - j\omega_m \boldsymbol{\psi_r} \tag{3}$$

$$\boldsymbol{\psi_s} = L_s \boldsymbol{i_s} + L_m \boldsymbol{i_r} \tag{4}$$

$$\boldsymbol{\psi_r} = L_m \boldsymbol{i_s} + L_r \boldsymbol{i_r}, \tag{5}$$

where R_s and R_r are the stator and rotor resistances, L_s, L_r and L_m are the stator, rotor and mutual inductances and ω_m is the rotor speed. The basic relation between torque and machine fluxes is:

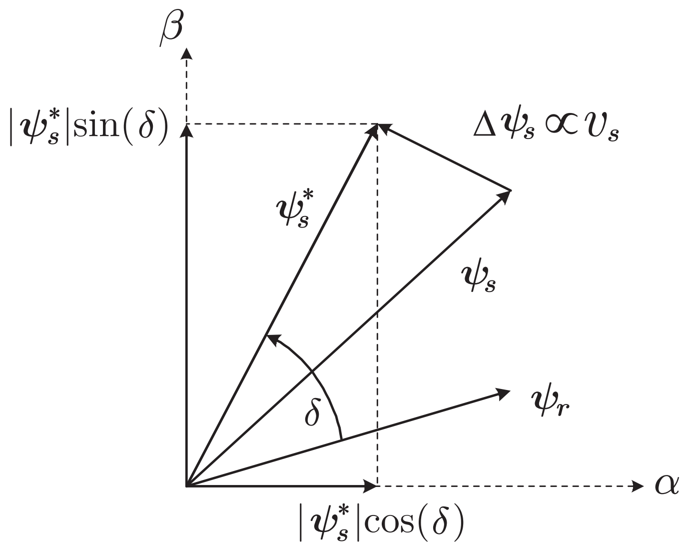

Fig. 1. Rotor flux ψ_r, reference and estimated stator flux ψ_s relations.

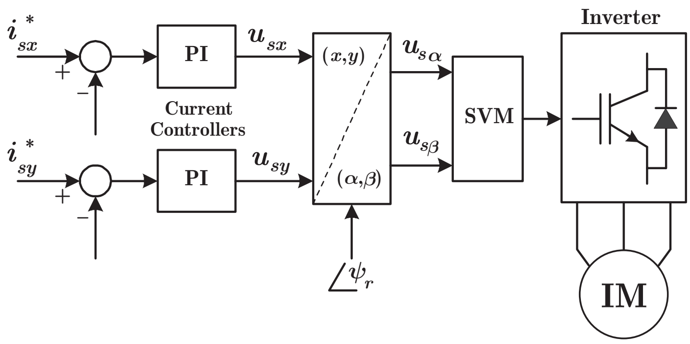

Fig. 2. Field Oriented Control block diagram.

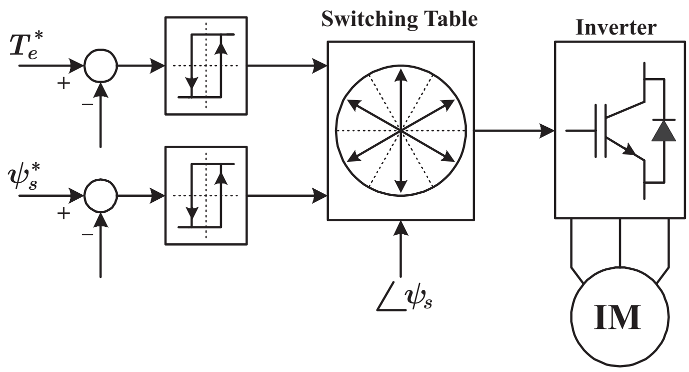

Fig. 3. Classic DTC control block diagram.

$$
\begin{aligned}
T_e &= \frac{3}{2}p\frac{k_r}{\sigma L_s}\boldsymbol{\psi_s}\times\boldsymbol{\psi_r} \\
&= \frac{3}{2}p\frac{k_r}{\sigma L_s}|\boldsymbol{\psi_s}|\cdot|\boldsymbol{\psi_r}|\sin(\delta),
\end{aligned} \tag{6}
$$

where δ, known as load angle, is the angle between stator and rotor fluxes as shown in Fig. 1, p is the number of pole pairs, $k_r = L_m/L_s$, and $\sigma = 1 - L_m^2/(L_s L_r)$. Based on (6) it is clear that it is possible to achieve machine speed and torque control directly by actuating over the load angle.

III. Field Oriented and Classic Direct Torque Control

A. Field Oriented Control

Field Oriented Control is based on the decomposition of the instantaneous stator current $\boldsymbol{i_s}$ into two orthogonal components in rotor flux oriented coordinates: one proportional to the flux (i_{sx}) and the other proportional to the torque (i_{sy}). Since both current vectors are perpendicular to each other, a decoupled dynamic system is obtained so that both variables can be controlled separately, achieving a similar operation principle as in DC-drives.

Fig. 2 illustrates a simplified control diagram of FOC. Both current components are controlled by individual PI controllers, which compute the corresponding stator voltage vector (v_{sx},v_{sy}) that will generate the desired correction in the current control loop. Then a coordinate rotation is performed to orient the variables respect the stator (α, β). Finally the desired stator voltage vector is generated using space vector modulation.

B. Direct Torque Control

Due to slow rotor flux dynamics, the easiest way to change the load angle is to force a change in the stator flux vector by the application of the appropriate stator voltage vector $\boldsymbol{v_s}$.

Neglecting the effect of the voltage drop on the stator resistance in (2), the stator flux vector is the time integral of the stator voltage vector. For sampling time Δt sufficiently small, (2) can be approximated by (7).

$$
\Delta\boldsymbol{\psi_s} \approx \Delta t \cdot \boldsymbol{v_s} \tag{7}
$$

In classic DTC the stator voltage selection is made by hysteresis comparators as shown in Fig. 3, with torque and flux magnitude errors as inputs and a predesigned gate-pulses look-up table that selects the stator voltage vector corresponding to the desired action.

This control strategy leads to changes from full negative torque to full positive causing high torque ripple. As demonstrated in [4], the capability to actuate on torque greatly depends on the emf $\omega_m\boldsymbol{\psi_s}$. This means that ripple frequency varies with rotor speed obtaining variable switching frequency and a wide spectrum for torque and stator current.

IV. Proposed Control Strategy

In the proposed method, the control objective is to select the exact stator voltage vector ($\boldsymbol{v_s}$) that changes $\boldsymbol{\psi_s}$ to meet the load angle reference, and so the desired torque while keeping flux amplitude constant. A space vector modulation algorithm is used to apply the required stator voltage vector. It is expected that torque ripple is almost eliminated, while zero steady state error is achieved with fixed switching frequency.

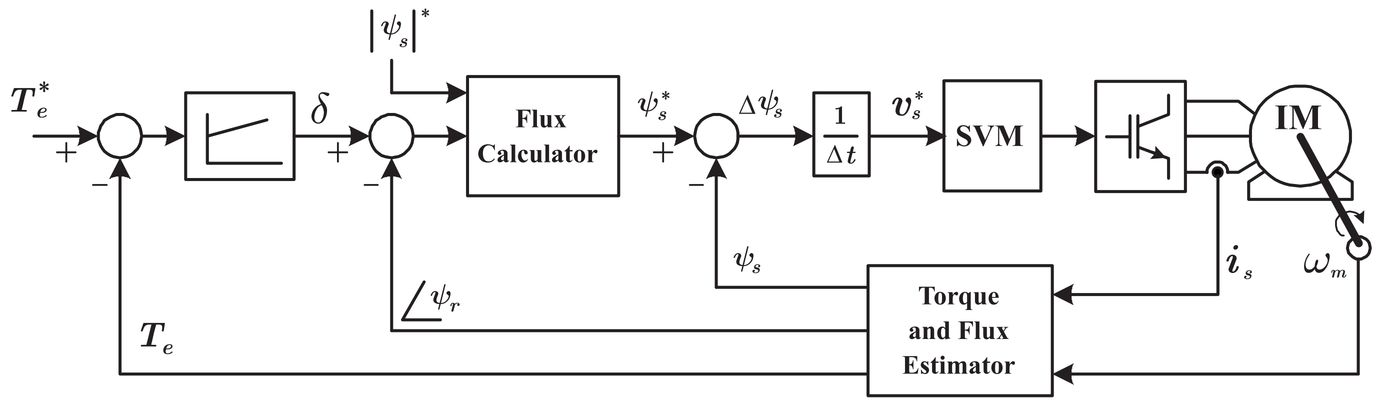

Fig. 4. Proposed DTC-SVM control scheme.

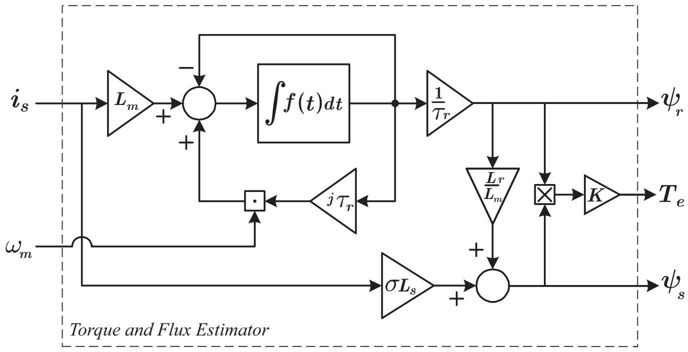

Fig. 5. Flux estimator block diagram.

The presented strategy uses one PI torque regulator, a simple flux calculation block and no rotating coordinate transformation making the control strategy a straightforward application of (6). This is illustrated by the control block diagram of Fig. 4. Here torque controller actuates over the load angle δ to meet torque reference tracking. The stator flux calculator block output is given by

$$\boldsymbol{\psi_s}^\star = |\boldsymbol{\psi_s}|^\star \cos\left(\delta + \angle\boldsymbol{\psi_r}\right) + j|\boldsymbol{\psi_s}|^\star \sin\left(\delta + \angle\boldsymbol{\psi_r}\right), \quad (8)$$

where $|\boldsymbol{\psi_s}|^\star$ is an arbitrary reference value. The use of rotor flux angle to obtain stator flux reference means that the proposed method is rotor oriented. The use of a rotatory reference frame aligned with rotor flux allows better torque-flux decoupling, leading to faster transient response.

According to the flux calculator output, the stator flux reference signal is compared with the estimated flux obtaining $\Delta\boldsymbol{\psi_s}$, that is needed to follow the torque reference, as it can be seen in Fig. 1. This value is divided by Δt to calculate $\boldsymbol{v_s}$ as in (7). The SVM block performs the classical space vector modulation of $\boldsymbol{v_s}$ to obtain the gate drive pulses for the power circuit.

V. Flux and Torque Estimator

To implement the stator and torque estimator block shown in Fig. 5 a rotor flux estimator based on the rotor model is implemented in stator coordinates by

$$\widehat{\boldsymbol{\psi}}_{\boldsymbol{r}} = \frac{1}{\tau_r}\int\left(L_m\boldsymbol{i_s} - (1-\tau_r j\omega_m)\,\widehat{\boldsymbol{\psi}}_{\boldsymbol{r}}\right)dt, \quad (9)$$

and the stator flux derived from

$$\widehat{\boldsymbol{\psi}}_{\boldsymbol{s}} = \sigma L_s\boldsymbol{i_s} + \frac{L_r}{L_m}\widehat{\boldsymbol{\psi}}_{\boldsymbol{r}}. \quad (10)$$

From these equations the flux estimator block gives the required rotor flux angle to be added to the reference stator flux signal. And the estimated stator flux needed to calculate $\Delta\boldsymbol{\psi_s}$.

Torque estimation is made from (6). Where the cross product can also be written as

$$\{\boldsymbol{\psi_s}\times\boldsymbol{\psi_r}\} = \psi_{s_\alpha}\psi_{r_\beta} - \psi_{s_\beta}\psi_{r_\alpha}. \quad (11)$$

Flux and torque estimator block diagram is shown in Fig. 5, where $K = 3/2p$. The feedback loop in the integration of the rotor model can compensate for finite time disturbances in the input $\boldsymbol{i_s}$ and unknown initial conditions.

VI. Results

Closed loop performance of the proposed method is tested and compared to classic direct torque control and field oriented control by means of speed reference tracking, torque dynamic response, flux control and signal spectrum.

A $5.5[kW]$, $380[V_{l-l}]$, two pole pairs induction machine is considered with $10[kHz]$ sampling frequency and $500[V]$ DC link voltage. A step change up to rated speed on the reference signal is applied in $t = 200[ms]$ at rotor speed $\omega_m = -150[rad/sec]$. The results are shown in Fig. 6.

In Fig. 6(a) the dynamic response using classic field oriented control is shown. Similarly, Fig. 6(b) shows the response with classic DTC. At the top of each figure the speed tracking reference is shown, torque response in the middle and stator flux magnitude at the bottom. Finally, similar results are presented for the proposed method in Fig. 6(c).

Figure 6 illustrates that field oriented control and the proposed method have similar dynamic responses, good speed reference tracking while keeping constant rotor flux amplitude for FOC and stator flux amplitude for the proposed DTC-SVM

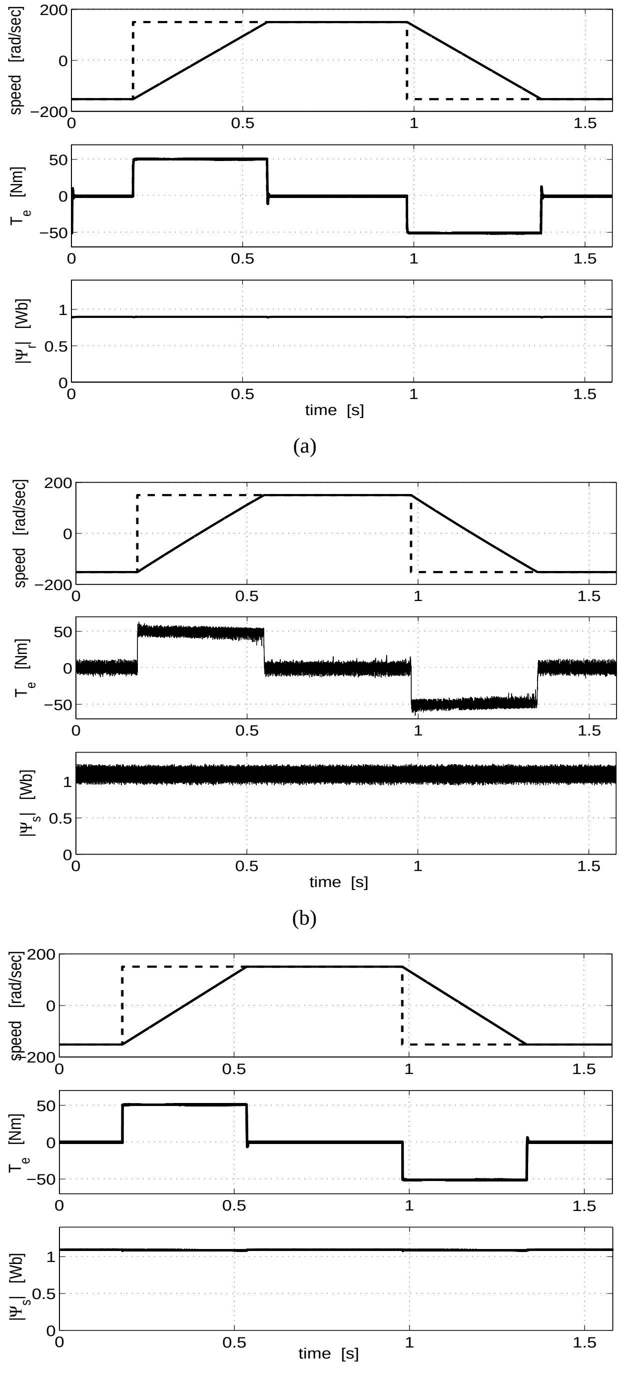

Fig. 6. Comparison of dynamic response between DTC-SVM, Field Oriented Control and Classic DTC. (a) Field Oriented Control, (b) Classic Direct Torque Control, (c) Proposed Method.

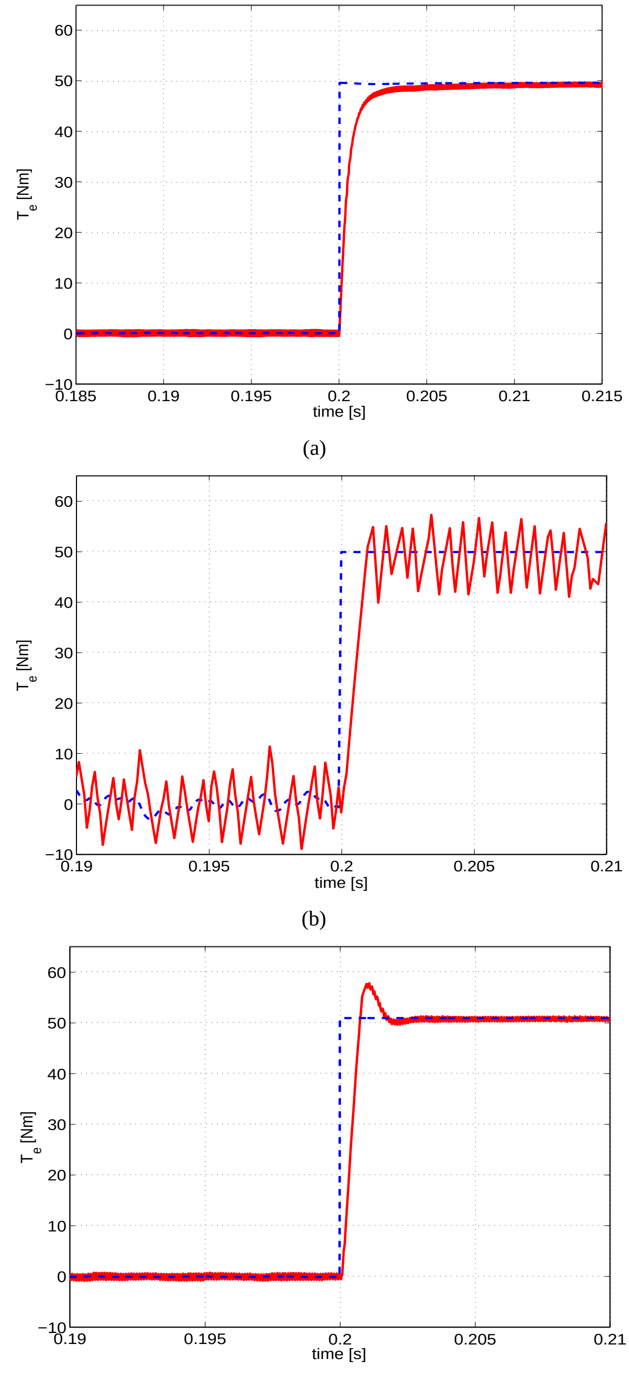

Fig. 7. Torque response comparison between DTC-SVM and classic DTC. (a) Field Oriented Control, (b) Classic Direct Torque Control, (c) Proposed Method.

method. Classic DTC shows high torque and flux ripple and similar rotor speed dynamic response as DTC-SVM and FOC.

To compare the fast dynamic torque response between the proposed method, FOC and classic DTC, the torque response to a step change in speed demand from negative to positive rated speed is analyzed. The results are shown in Fig. 7. It is clear that the DTC-SVM improves classic DTC torque reference tracking, reducing torque ripple, achieving zero steady state error and obtaining a torque response almost as fast as classic DTC. In Fig. 7(a) FOC torque step response is shown. It can be seen that the inner current loop dynamics have an important role in the torque response.

It is important to remark that in classic DTC torque ripple as big as in Fig. 7(b) can not be reduced by simply reducing torque hysteresis band. The high torque change rate hinders the detection of the hysteresis band crossing unless high sample frequency is used. The effect of a reduced hysteresis band in the torque ripple can be observed in Fig. 8 top, where a

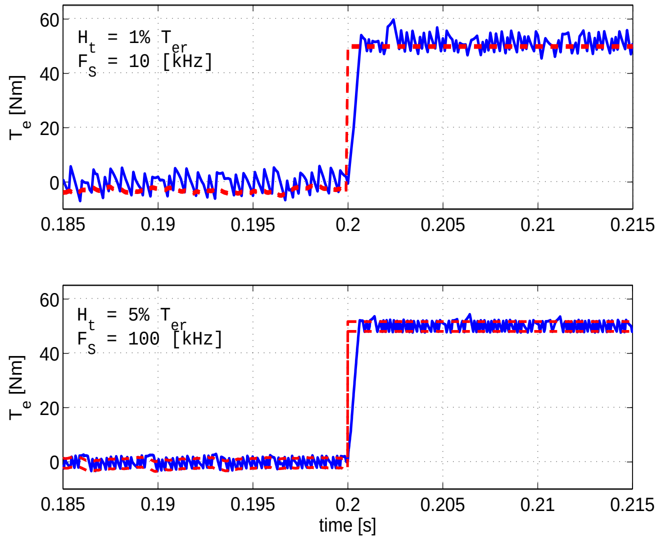

Fig. 8. Size of hysteresis band and sampling frequency effects on torque ripple for classic DTC.

band of 1% rated torque has been used maintaining the same sample frequency as before. It can be seen that there are not important differences with figure 7(b). On the other hand, in Fig. 8 bottom increased sampling frequency was used while keeping the band to its original 5% value, effectively reducing the torque ripple. It may be concluded then, that the only way to improve classic DTC performance is to increase sampling frequency, this is normally not possible due to constraints on the switching frequency and minimum computational time requirements.

A major advantage of the proposed DTC-SVM method over classic DTC is that the use of a voltage modulator leads to fixed switching frequency, equal to sample frequency. Fig. 9(a) shows torque spectral analysis with the proposed method and Fig. 9(b) shows a typical spectral content using classic DTC. The energy of torque harmonics in classic DTC is distributed in a wide range of frequencies. This can generate resonances and undesirable acoustic noise. In the proposed method the spectral energy is concentrated at sample frequency harmonics.

Although, the proposed method controls stator flux, Figure 10 shows three-phase stator currents response during the speed change, here the sinusoidal current waveform is clear, showing that good current control is inherent to the algorithm.

VII. Conclusions

The DTC-SVM strategy proposed in this work to control flux and torque is based on few induction machine fundamental equations. Consequently, the control method is simple and easy to implement. No coordinate rotation and less PI controllers than in field oriented control are needed. In addition, the proposed DTC strategy is well suited for use in conjunction with space vector modulation resulting in a powerful alternative to overcome the well known drawbacks of the original DTC solution: variable switching frequency and high torque ripple.

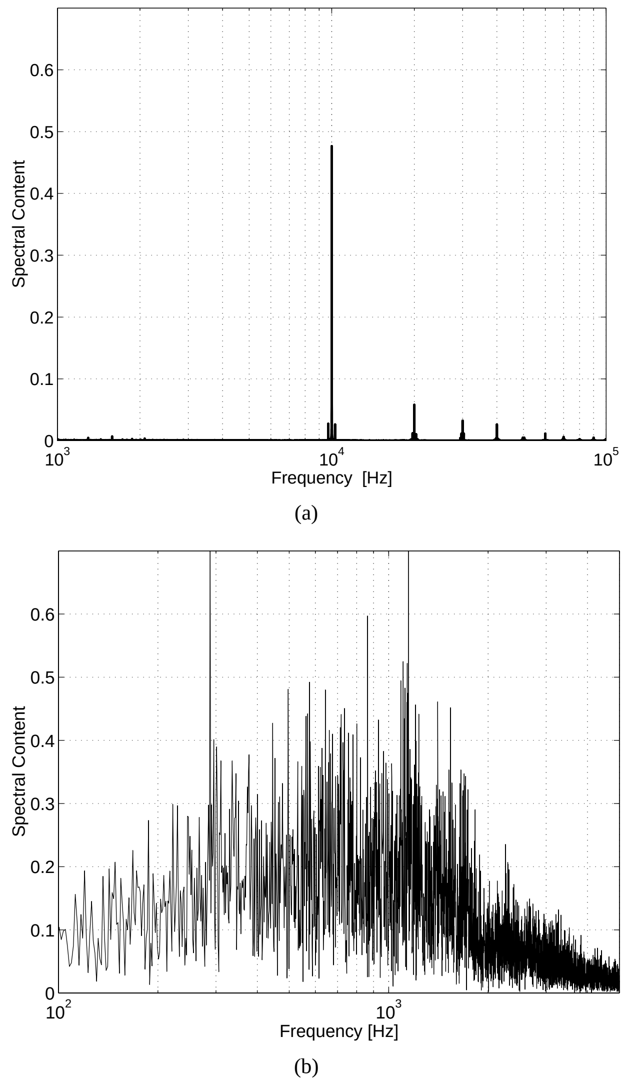

Fig. 9. Torque spectral analysis comparison. (a) DTC-SVM torque spectrum, (b) Classic DTC torque spectrum.

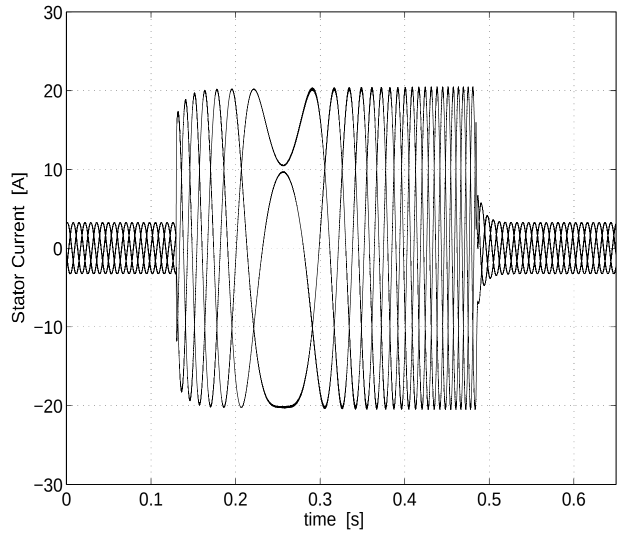

Fig. 10. Stator Current during speed reversal.

APPENDIX

Motor parameters used to test and compare the proposed control strategy are given in table I.

TABLE I
MOTOR PARAMETERS

Parameter	Value
R_s [Ω]	3.102
R_r [Ω]	4.046
L_s [Hy]	0.337
L_r [Hy]	0.337
L_m [Hy]	0.322
p	2
J [rad/Nms]	0.06
power [KW]	5.5
V_{RMS}	380

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