A Discrete Space Vector Modulation Direct Torque Control of Sensor less Induction Machines

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Abstract— In this paper, we present a Direct Torque Control scheme of an induction motor operating without speed sensor. The estimation of the stator flux and the rotor speed is performed by an adaptive observer. In order to reduce the torque, flux, current and speed ripple a Discrete Space Vector Modulation (DSVM-DTC) strategy is implemented using a DSP-based hardware. To illustrate the performances of this control scheme, experimental results are presented.

Index Terms— Adaptive Observer, Direct Torque Control, Induction Motor, Space Vector Modulation.

I. INTRODUCTION

Alternating current motors are getting more and more popular for applications in industrial environments. Particularly in speed control systems, ac induction motors are more widely used nowadays due to the characteristics of higher efficiency, less inertia, smaller volume and lower cost. Moreover, in contrast to dc motors, induction motors can be used for a long time without maintenance because of their brushless structures. The capabilities to operate at higher speeds, higher torques and larger power ratings make the induction motors more attractive than dc motors for medium and high power motor drives.

In recent years, research interest in IM sensor less drives has grown significantly due to some of their advantages, such as mechanical robustness, simple construction and maintenance [1]. Present efforts are devoted to improve the sensor less operation, especially for low speed and to develop robust control strategies.

The DTC is one of the actively researched control schemes which is based on the decoupled control of stator flux and torque providing a quick and robust response with a simple control construction in ac drives. However, the conventional DTC strategy using only one switching table at high and low speed present notable torque, flux, current and speed ripple.

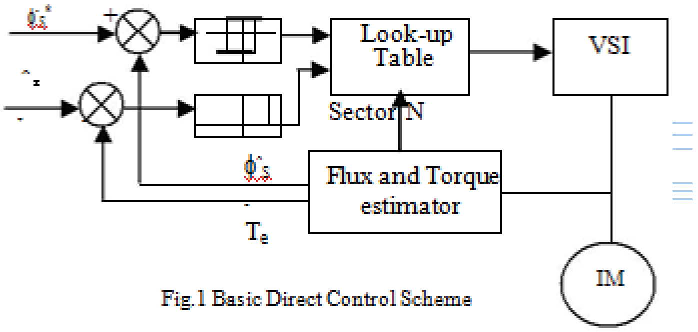


Fig.1 Basic Direct Control Scheme

This paper presents a sensor less induction motor control scheme using an adaptive observer for the stator flux and the rotor speed estimation based on discrete space vector modulation (DSVM-DTC) switching strategy.

II. DIRECT TORQUE CONTROL

Direct Torque Control (DTC) was proposed by M. Depenbrock and I. Takahashi. This method presents the advantage of a very simple control scheme of stator flux and torque by two hysteresis controllers, which give the input voltage of the motor by selecting the appropriate voltage vectors of the inverter through a look-up-table in order to keep stator flux and torque within the limits of two hysteresis bands as shown in Fig.1. The application of this principle allows a decoupled control of flux and torque without the need of coordinate transformations, PWM pulse generators and current regulators. Different voltage vector selection criteria can be employed to control the torque according to whether the flux has to be reduced or increased, leading to different switching tables. Very high dynamic performance can be achieved by DTC, however, the presence of hysteresis controllers leads to a variable inverter switching frequency operation. In addition, the time discretization, due to digital implementation, plus the limited number of available voltage vectors is source of large current and torque ripple, causing the deterioration of the steady performance especially in low speed range.

In order to improve the steady performance, different DTC strategies have been proposed to perform constant switching frequency operation and to decrease the torque ripple. In general, they require more complex control schemes in comparison to the basic DTC ones

III. FLUX AND TORQUE CONTROL

With reference to current and torque ripple, it has been verified that a large influence is exerted by the amplitude of the flux and the torque hysteresis bands, and the voltage vector selection criteria. It can be noted also that a given voltage vector has a different effect on the drive behaviour at high and low speed. Taking these considerations into account, a good compromise has been obtained using different switching tables at high and low speed. In general, the determination of the switching tables is carried out on the basis of physical considerations concerning the effects determined by radial and tangential variations of the stator flux vector on torque and flux values.

A substantial reduction of current and torque ripple could be obtained using, at each cycle period, a preview technique in the calculation of the stator flux vector variation required to exactly compensate the flux and torque error. In order to apply this principle, the control system should be able to generate, at each sampling period, any voltage vector. This ideal behaviour can be approximated using a control system able to generate a number of voltage vectors higher than that used in basic DTC scheme. These solutions are good for high power applications, but are not acceptable for medium or low power applications cause to the increased complexity of the power circuit.

IV. DSVM-DTC CONTROL STRATEGY

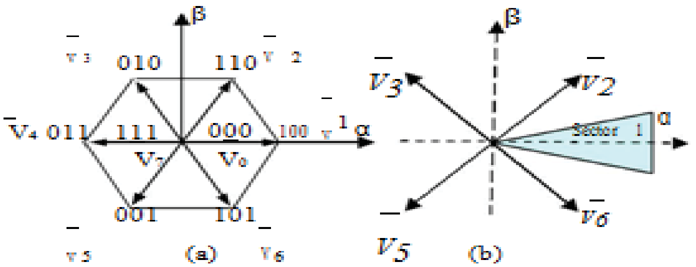
The main idea the DSVM-DTC control strategy is to force the torque and stator flux to approach their reference by applying in one sampling period several voltage vectors instead of only one voltage vector as in basic DTC.

This control algorithm uses prefixed time intervals within a cycle period and in this way a higher number of voltage space vectors can be synthesized with respect to those used in basic DTC technique [4]. The increased number of voltage vectors allows the definition of switching tables according to the rotor speed (Fig. 2e), the flux and torque errors. The switching tables are derived from the analysis of the equations linking the applied voltage vector to the corresponding torque and flux variations.

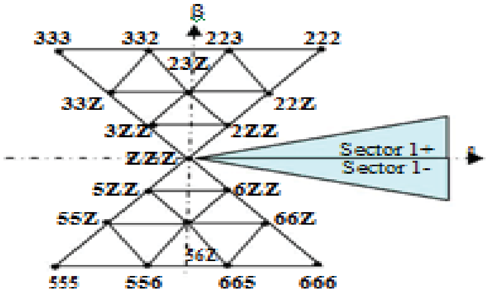
To understand the principle of the DSVM-DTC control strategy, let us take, for example, the case when the stator flux is located in sector 1, in basic DTC five voltage vectors can be selected (Fig. 2b) and a single voltage vector is applied during the whole switching period. When the flux or torque error is big positive or negative the application of Single voltage vector during the whole switching period assures quick response. However, if the errors are small the application of a single voltage vector can cause great variation of flux or torque and it can be source of ripple.

With DSVM-DTC strategy, 19 voltage vectors can be selected for each sector, according to the rotor speed, the flux and the torque errors range as is represented in Fig. 2c and TABLE I. The switching period is divided into three equal time intervals and one voltage vector is applied at each time interval.

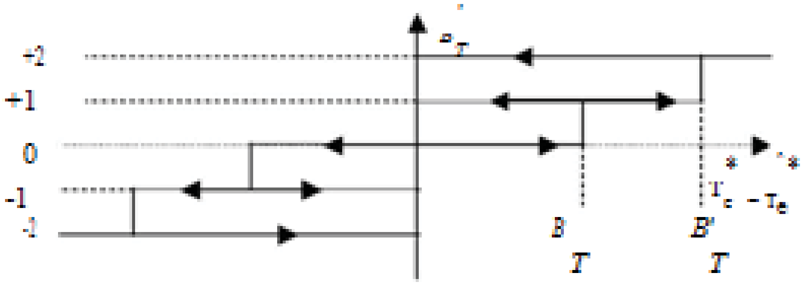
For example, the label "23Z" denotes the voltage vector which is synthesized by using the voltage space vectors V2, V3 and V0 or V7, each one applied for one third of the cycle period.



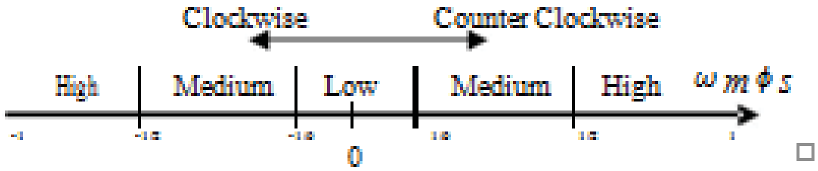
(a) Voltage vectors obtained by two level VSI
(b) Voltage vectors selection in basic DTC



(c) Voltage vectors selection in DSVM-DTC strategy for sector 1



(d) Five level torque hysteresis comparator



(e) Emf range subdivision in p.u. of the rate voltage Fig 2 DSVM-DTC strategy scheme

TABLE I: Voltage vectors selection in DSVM-DTC strategy for sector 1 and Counter Clockwise rotor speed

<table>
<tr><th colspan="7">Low emf range</th></tr>
<tr><td>C_ϕ</td><td>C_T</td><td>-2</td><td>-1</td><td>0</td><td>1</td><td>2</td></tr>
<tr><td colspan="2">0</td><td>555</td><td>5ZZ</td><td>ZZZ</td><td>3ZZ</td><td>333</td></tr>
<tr><td colspan="2">1</td><td>666</td><td>6ZZ</td><td>ZZZ</td><td>2ZZ</td><td>222</td></tr>
<tr><th colspan="7">Medium emf range</th></tr>
<tr><td>C_ϕ</td><td>C_T</td><td>-2</td><td>-1</td><td>0</td><td>1</td><td>2</td></tr>
<tr><td colspan="2">0</td><td>555</td><td>ZZZ</td><td>3ZZ</td><td>33Z</td><td>333</td></tr>
<tr><td colspan="2">1</td><td>666</td><td>ZZZ</td><td>2ZZ</td><td>22Z</td><td>222</td></tr>
<tr><th colspan="7">High emf range sector 1+</th></tr>
<tr><td>C_ϕ</td><td>C_T</td><td>-2</td><td>-1</td><td>0</td><td>1</td><td>2</td></tr>
<tr><td colspan="2">0</td><td>555</td><td>3ZZ</td><td>33Z</td><td>333</td><td>333</td></tr>
<tr><td colspan="2">1</td><td>666</td><td>2ZZ</td><td>23Z</td><td>223</td><td>222</td></tr>
<tr><th colspan="7">High emf range sector 1-</th></tr>
<tr><td>C_ϕ</td><td>C_T</td><td>-2</td><td>-1</td><td>0</td><td>1</td><td>2</td></tr>
<tr><td colspan="2">0</td><td>555</td><td>3ZZ</td><td>23Z</td><td>332</td><td>333</td></tr>
<tr><td colspan="2">1</td><td>666</td><td>2ZZ</td><td>22Z</td><td>222</td><td>222</td></tr>
</table>

V. ADAPTIVE FLUX AND SPEED OBSERVER

In this section we present the global structure of the observer under study, which is based on the induction motor model written in stator reference frame [5]. The motor model is given by:

$$\frac{d}{dt}\begin{bmatrix} i_s \\ \phi_r \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}\begin{bmatrix} i_s \\ \phi_r \end{bmatrix} + \begin{bmatrix} \boldsymbol{B}_1 \\ 0 \end{bmatrix} v_s = \boldsymbol{A}x + \boldsymbol{B}v_s$$

$$i_s = \boldsymbol{C}x$$

where

$i_s = [i_{ds} i_{qs}]^T$ stator current

$\phi_r = [\phi_{dr} \phi_{qr}]^T$ rotor flux

$v_s = [v_{ds} v_{qs}]^T$ stator voltage

$$A_{11} = -\{R_s/(\sigma L_s) + (1-\sigma)/(\sigma\tau_r)\}\boldsymbol{I} = a_{r11}\boldsymbol{I}$$

$$A_{12} = M/(\sigma L_s L_r)\{(1/\tau_r)\boldsymbol{I} - \omega_r \boldsymbol{J}\} = a_{r12}\boldsymbol{I} + a_{i12}\boldsymbol{J}$$

$$A_{21} = (M/\tau_r)\boldsymbol{I} = a_{r21}\boldsymbol{I}$$

$$A_{22} = -(1/\tau_r)\boldsymbol{I} + \omega_r \boldsymbol{J} = a_{r22}\boldsymbol{I} + a_{i22}\boldsymbol{J}$$

$$B_1 = 1/(\sigma L_s)\boldsymbol{I} = b_1 \boldsymbol{I}$$

$$\boldsymbol{C} = [\boldsymbol{I} \;\; 0]$$

$$\boldsymbol{I} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \qquad \boldsymbol{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

R_s, R_r	stator and rotor resistance
L_s, L_r	stator and rotor self inductance
M	mutual inductance
σ	leakage coefficient, $\sigma = 1 - M^2/(L_s L_r)$
τ_r	rotor time constant, $\tau_r = L_r/R_r$
ω_r	motor angular velocity

ω_r : is the rotor mechanical speed.

A linear state observer for the rotor flux can then be derived as follows by considering the mechanical speed as a constant parameter since its variations are very slow in comparison to those of the electrical variables:

$$\dot{\hat{x}} = A\hat{x} + Bu + K\left(y - \hat{y}\right) \qquad (2)$$

The symbol ^ denotes an estimated quantity. *K* is a gain matrix, which is used to suitably locate the observer's poles.Using Lyapounov stability theory, we can construct a mechanism to adapt the mechanical speed from the asymptotic convergence's condition of the state variables estimation errors**:**

$$\hat{\omega}_s = -K_{i\omega}\int (e_{s\alpha}\hat{\phi}_{r\alpha} + e_{s\beta}\hat{\phi}_{r\beta})dt - K_{p\omega}(e_{s\alpha}\hat{\phi}_{r\alpha} + e_{s\beta}\hat{\phi}_{r\beta}) \qquad (3)$$

Where $e_{s\alpha} = i_{s\alpha} - \hat{i}_{s\alpha}$ and $e_{s\beta} = i_{s\beta} - \hat{i}_{s\beta}$.

$K_{i\omega}$ and $K_{p\omega}$: are positive gains.

The voltage drop over the stator resistance at low rotor speed reduces the amplitude of the stator flux remarkably. In order to improve the estimation precision of both flux and speed variables, we included an adaptation mechanism of the stator resistance [6], which is subject to drift due to motor heating. In the same manner that for the speed variable, the stator resistance estimate is given by:

$$\hat{R}_s = -K_{ir}\int (e_{s\alpha}\hat{i}_{\alpha s} + e_{s\beta}\hat{i}_{\beta s})dt - K_{pr}(e_{s\alpha}\hat{i}_{\alpha s} + e_{s\beta}\hat{i}_{\beta s}) \qquad (4)$$

Fig. 3 presents the global adaptive observer structure.

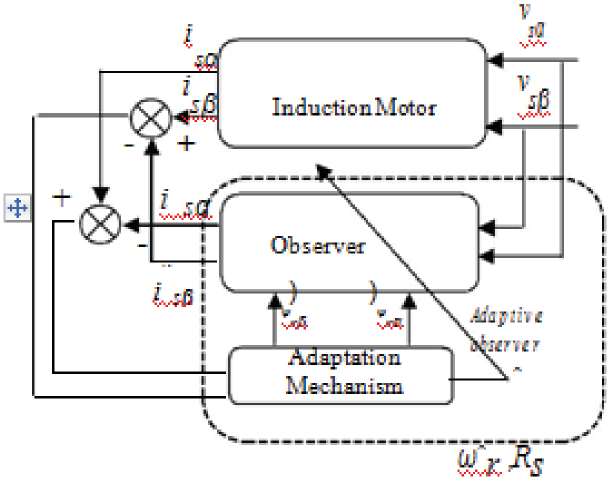


Fig. 3 Global adaptive observer structure

VI. EXPERIMENTAL RESULTS

The configuration of the experimental system used to validate the proposed control algorithm is shown in Fig. 4, it is made up of a 1Kw/380/50Hz squirrel cage induction motor fed by a 2-level IGBT voltage source inverter and digital signal processor (DSP) control board.

The whole control algorithm (Adaptive speed and flux observer, stator resistance tuning, DTC algorithm and PI speed regulator) is implemented in a single fixed-point TMS320F240 DSP-based development board from Texas Instruments within less than 100µs of time computing. The digital control signals of the power components are generated by the DSP-controller via PWM outputs. The control frequency is about 10Khz. Voltage and current variables are measured by Hall-effect sensors and sampled at the same frequency. A mechanical speed tachometer is mounted on the motor's shaft only to allow comparison between estimated and measured speed. The tachometer's signal is not used in the closed-loop speed control.

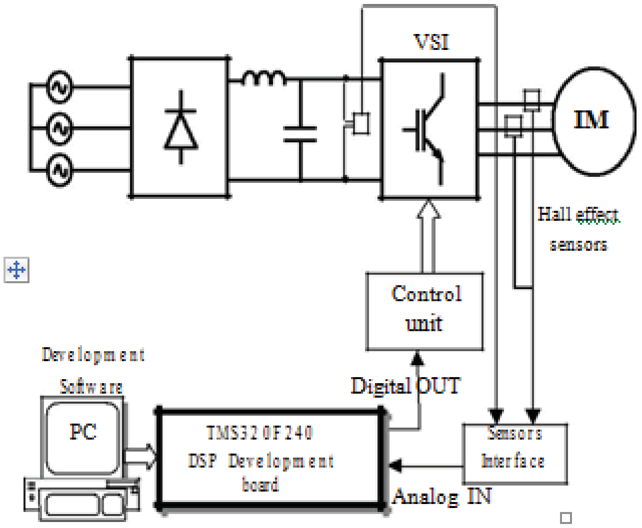


Fig. 4 Experimental system scheme

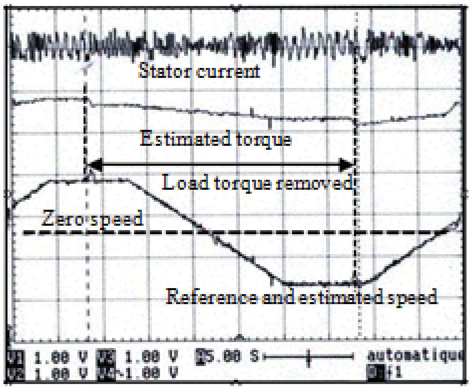
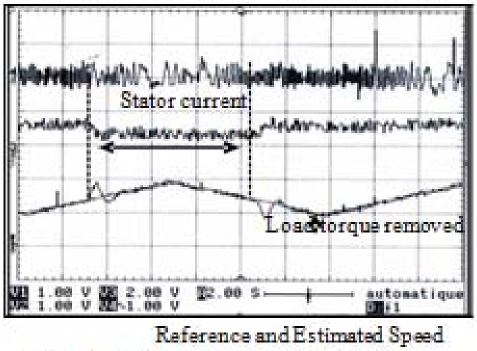


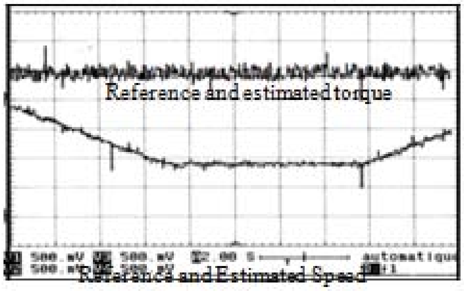
Fig.5 Current, Torque and Speed responses for speed reversal operation from 1500rpm to -1500rpm

A series of experimental results are depicted on figures 5, 6 and 7, which represent the performances of the flux and speed adaptive observer under several conditions in association with the DSVM-DTC strategy and the stator resistance tuning. They prove the effectiveness of the adaptive observer in general and especially in association with the DSVM-DTC strategy, even without the stator resistance tuning. The whole control algorithm was implemented on a single DSP-controller board within a reasonable computing time, which gives result to a good performance/ease of implementation ratio.

Fig. 5 shows a small ripple in the stator current, the estimated torque and the rotor speed responses without stator resistance tuning, when the speed command is changed from 1500 rpm to -1500rpm. However, Fig. 6 present notable torque and speed ripple at low speed (100rpm). Fig.7, shows a good torque and speed responses with stator resistance tuning at low speed (100rpm).



(a) Torque and speed responses at transient state with stator resistance tuning



(b) Torque and speed responses at steady state with stator resistance tuning

Fig.7 Current, Torque and Speed responses with stator resistance tuning at low speed (100rpm) and rated load (2Nm*)*

VII. SIMULATION RESULTS

To confirm the effectiveness of the proposed DSVM technique based vector controlled induction motor drive, simulation studies have been carried out and results are presented. For the numerical simulation studies the induction motor parameters are taken as R_s=1.57Ω, R_r=1.21Ω, L_m=0.165H, L_s=0.17H, L_r=0.17H and J=0.089Kg-m^2. The simulation results of conventional vector controlled induction motor drive are shown in Fig.5-Fig.10. The simulation results of proposed DSVM based vector controlled induction motor drive are shown from Fig. 11 to Fig. 16. From the simulation results, it can be concluded that the proposed DSVM based vector control algorithm gives fast transient response like conventional vector control algorithm. From the steady state simulation results and harmonic spectra of line currents, it can be concluded that the proposed DSVM based vector control algorithm gives reduced harmonic distortion when compared with the conventional vector control algorithm.

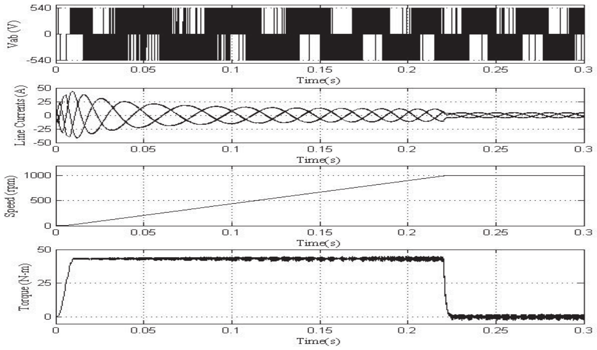
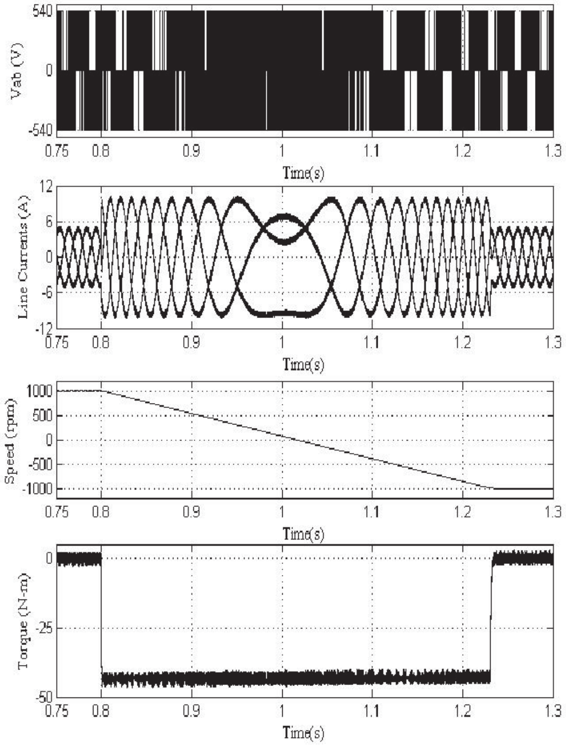


Fig. 1 starting transients of classical vector control algorithm based induction motor drive



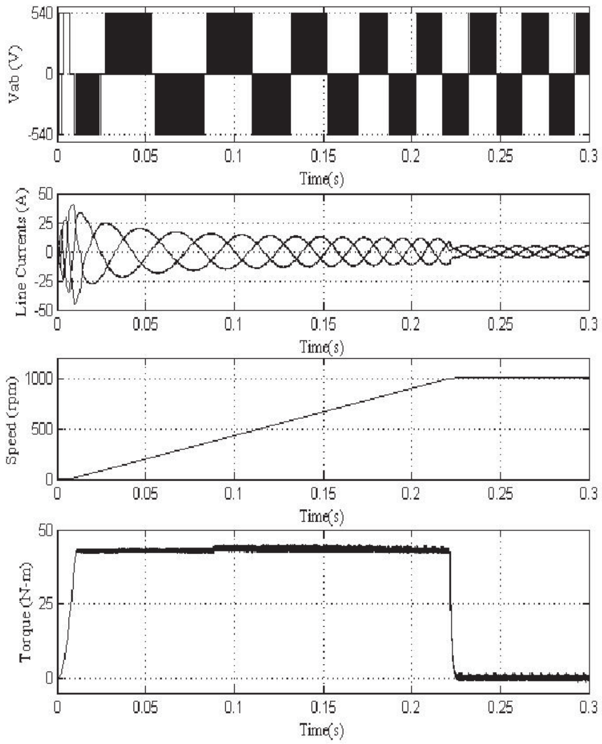


Fig. 5 Transients during the speed reversal (from +1000 rpm to -1000 rpm) for classical vector control algorithm based induction motor drive.

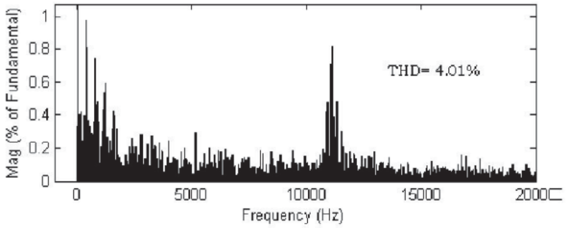


Fig. 6 Harmonic spectra of stator current in DSVM algorithm based vector controlled induction motor drive

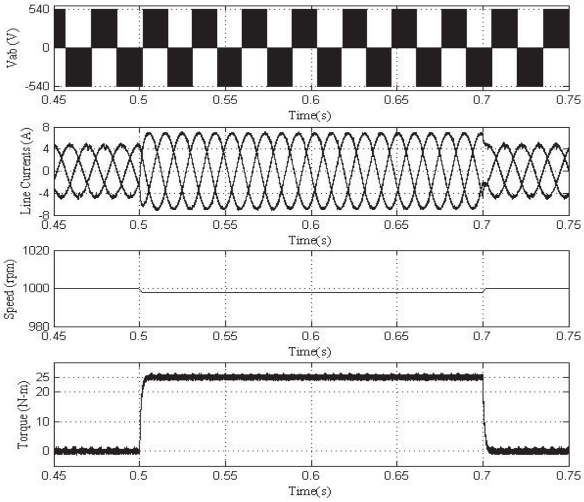


Fig. 10 Transients during the step change in load (a 25 N-m load is applied at 0.5 sec and removed at 0.7 sec) for DSVM algorithm based vector controlled induction motor drive

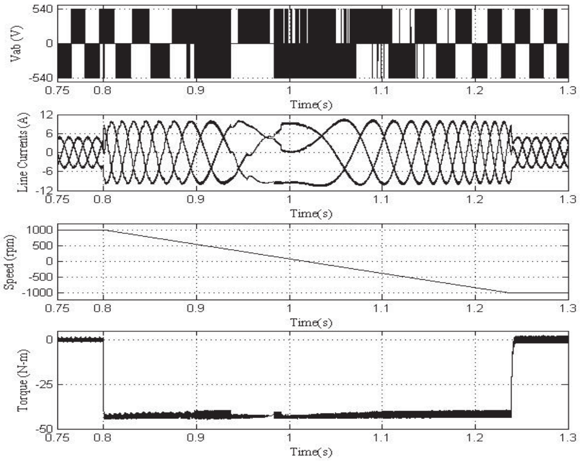


Fig. 11 Transients during the speed reversal (from +1000 rpm to -1000 rpm) for DSVM algorithm based vector controlled induction motor drive

APPENDIX

Induction motor data

1Kw	Rated power.
2830rpm	Rated speed.
220v	Rated voltage.
4.67Ω	Stator resistance.
8Ω	Rotor resistance.
0.347 H	Stator inductance.
0.374 H	Rotor inductance.
0.366 H	Mutual inductance.
0.003 Kg.m^2	Motor-Load inertia
1	# of pole pairs.

VII. CONCLUSION

This paper presents an induction motor drive technique using the DSVM-DTC strategy. Experimental performance analysis of an adaptive stator flux and speed observer with stator resistance tuning, performed by a DSP controller. The analysis focuses both on transient and static characteristics. They prove the effectiveness of the adaptive observer in general and especially in association with the DSVM-DTC strategy. With the experimental results it has been verified that the DSVM-DTC strategy allows the torque, the rotor speed and the current ripple to be reduced in comparison to the basic DTC strategy.

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