Direct Torque Control of Sensorless Induction Motor Based on Space Vector modulation and Sliding Mode Flux Observer

Abdelkarim AMMAR
Electrical engineering Laboratory
University Of Mohammed Khider Biskra
Biskra, Algeria
Ammar.abdelkarim@yahoo.fr

Amor BOUREK
Electrical engineering Laboratory
University Of Mohammed Khider Biskra
Biskra, Algeria
Bourek_amor@hotmail.com

Abdelhamid BENAKCHA
Electrical engineering Laboratory
University Of Mohammed Khider Biskra
Biskra, Algeria
ab.benakcha@gmail.com

***Abstract*—Direct Torque Control (DTC) is an AC drive's control strategy used to achieve a decoupled torque and flux control. The conventional DTC utilizing hysteresis comparators suffers from high torque ripples and variable switching frequency. The most common solution to those problems is to use the space vector modulation. In this paper a modified direct torque control of induction motor scheme is presented. The modifications include torque and flux ripples reduction. This technique is known as SVM-DTC. It is based on stator flux orientation and space vector modulation (SVM). In the other hand this paper aims to design a sliding mode observer for speed/flux estimation which improves the control performances by using a sensorless algorithm in order to decrease the cost and reliability of the system. The theoretical principles, simulation and experimental results of sensorless control method are presented using Matlab/Simulink with real time environment using dSpace 1104.**

Key words— Induction Motor, DTC, SVM, Sliding Mode Observer, Ds 1104

I. INTRODUCTION

Direct Torque Control (DTC) was proposed by Takahashi and Depenbrock [1],[2]. This method presents the advantage of a very simple control scheme of stator flux and torque, which give the input voltage of the motor by selecting the appropriate voltage vectors of the inverter through switching table. However, the main problem of this method is the high level of torque ripple and variable switching frequency of the inverter. For overcome this drawbacks a voltage modulation is implemented and replacing the switching table of the voltage vector selection [3], it based on space vector modulation (SVM) with constant switching frequency. The control methods using SVM-DTC can take different structures and we mention among them: stator flux oriented control (SFOC) with SVM uses two (PI) controllers instead of hysteresis controllers for generating direct and quadrature voltage components [3], [4]. Other method is applied in this paper known as closed loop torque control, based on changes on motor's torque and achieves an appropriate voltage vector[5][6] and unlike the previous, this method uses only one PI controller.

Another point of this paper is the presentation of sensorless algorithm for flux, torque and speed estimation in order to reduce the number of sensors and the control system's cost of realization and installation [7][11]. In this context, the sliding mode methodology, capable of guaranteeing high levels of robustness against disturbances and parameters variations, seems to be well applicable to the design of both the observers and the controllers. Indeed, the use of sliding mode based solutions is widely discussed in the literature [8].

To increase the accuracy in a wide speed range operation and to reduce the complexity, an inherently sensorless observer is presented and without using rotor speed as adaptive quantity contrary to speed adaptive sliding-mode observers, Luenberger observers or extended Kalman filters, where usually, the speed estimation is the last step of the estimation process, and it is affected by noise and errors [9], [10].

The main goal of this paper is to present sensorless SVM-DTC based on load angle with inherently SMO used for flux, torque and speed reconstruction. The results are examined under simulation and experimental environment.

II. LOAD ANGLE BASED DTC STRATEGY USING SVM

A. Load Angle DTC strategey

In this control scheme, the torque of the motor can be adjusted by controlling load angle δ change which is the angle between stator and rotor flux vectors, this algorithm called also closed loop torque control where the torque of induction motor can be expressed in terms of stator and rotor flux vectors as:

$$T_e = p\frac{M_{sr}}{\sigma L_s L_r}\psi_s \times \psi_r = p\frac{M_{sr}}{\sigma L_s L_r}|\psi_s||\psi_r|\sin(\delta) \qquad (1)$$

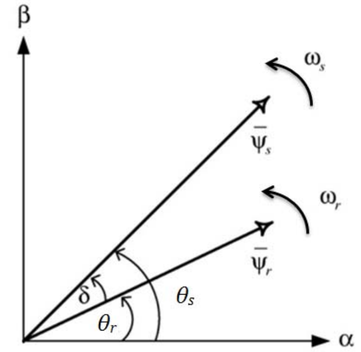


Fig.1. Stator and rotor flux vectors and angles.

Where:
p: Number of pole pairs
ψ_s, ψ_r Stator and rotor value
θ_s, θ_r: Stator and rotor flux angles
δ: Torque angle

The main object of this latter is to select the stator voltage vector V_s that changes ψ_s and modulate it by SVM technique, the produced change in angle by torque controller is added in the actual angle of stator flux vector, so we can estimate the reference stator flux vector by the following formula (9), it's polar-to rectangular transformation [6],[14].

$$\psi_s^* = |\psi_s^*|\cos(\delta + \theta_r) + j|\psi_s^*|\sin(\delta + \theta_r) \qquad (2)$$

The reference stator voltages ($V_{s\alpha}, V_{s\beta}$) that changes the rotating speed of stator flux vector to generate required torque while keeping its amplitude constant are calculated based on the stator flux error and sampling time in *(α, β)* frame and given by :

$$\begin{cases} V_{s\alpha} = \dfrac{\psi_{s\alpha}^* - \hat{\psi}_{s\alpha}}{\Delta T} + R_s i_{s\alpha} \\ V_{s\beta} = \dfrac{\psi_{s\beta}^* - \hat{\psi}_{s\beta}}{\Delta T} + R_s i_{s\beta} \end{cases} \qquad (3)$$

Where: $\Delta T = T_s$ Sampling time period

Fig.2 shows the global block diagram of the closed loop torque DTC. The SVM algorithm is applied to achieve fixed switching frequency.

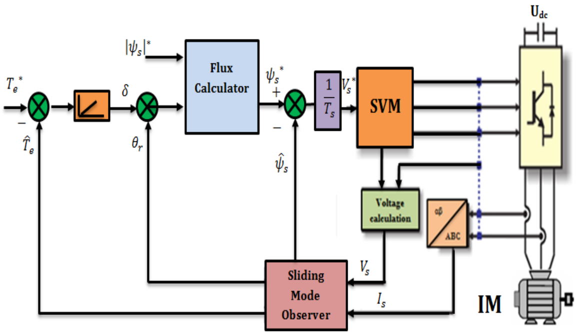


Fig.2. Modified Direct Torque Control based on load angle control scheme.

III. Sliding Mode Flux Observer

A. Sliding Mode Observer Design

In this paper the objective of the sliding mode observer is to build the components of the stator flux and use them for torque and speed estimation, based on the state model of induction motor in the rotor reference frame [9] that has the stator flux ψ_s and the stator current i_s as state variables.

$$\begin{cases} \dfrac{d\psi_s}{dt} = -R_s i_s - j\omega_r \psi_s + u_s & (4) \\ \dfrac{di_s}{dt} = -\dfrac{1}{\sigma}\left(\dfrac{1}{T_r} + \dfrac{1}{T_s}\right) i_s + \dfrac{1}{\sigma L_s}\left(\dfrac{1}{T_r} - j\omega_r\right)\psi_s \\ +\dfrac{1}{\sigma L_s} u_s & (5) \end{cases}$$

The state model contains back-emf ($\omega_r \psi_s$). In this observer all these terms with rotor speed are considered as disturbances. Then an inherently observer (Fig. 3) can be express as:

$$\begin{cases} \dfrac{d\hat{\psi}_s}{dt} = -R_s i_s + u_s - Ksign(S) & (6) \\ \dfrac{d\hat{i}_s}{dt} = -\dfrac{1}{\sigma}\left(\dfrac{1}{T_r} + \dfrac{1}{T_s}\right)\hat{i}_s + \dfrac{1}{\sigma L_s T_r}\hat{\psi}_s + \dfrac{1}{\sigma L_s} u_s \\ -\dfrac{1}{\sigma L_s} Ksign(S) & (7) \end{cases}$$

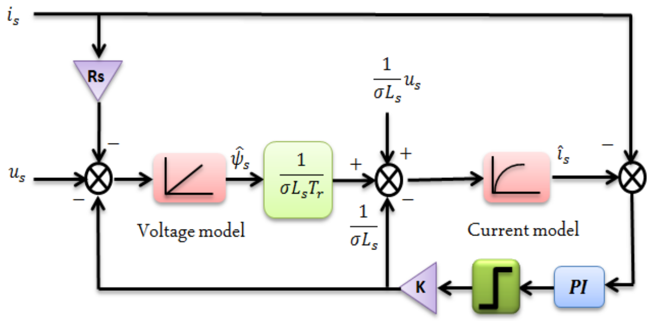


Fig.3. Inherently Sliding mode stator flux observer

K is the observer gain, *S* is sliding surface of the current error. *PI* controller is proposed to impose desired error convergence where:

$$S = (K_p + \frac{K_i}{s})(\hat{i}_s - i_s) \qquad (8)$$

The observer gain has to be large enough under stability condition from Lyapunov analysis.

$$L = \frac{1}{2} e^T e \qquad (9)$$

By using Lyapunov candidate function that defined in (9) and IM and SMO models (4), (5), (6), (7) and during sliding mode $S = 0, \frac{dS}{dt} = 0$, *K* is given as:

$$K > \max\left(\left|\frac{e_{\psi_{s\alpha}}}{T_r} - \omega_r \psi_{s\beta}\right|\left|\frac{e_{\psi_{s\beta}}}{T_r} - \omega_r \psi_{s\alpha}\right|\right) \qquad (10)$$

Where:

$e_{\psi_{s\alpha\beta}}$: Flux error

B. Chattering phenomenon

In sliding mode technique an infinite commutation causes the chattering phenomenon and it is undesirable in practice, in order to reduce this problem the traditional sign function is replaced by a softer one related to saturation function $Sat(S)$ [12].

$$Sat(S) = \begin{cases} 1 & if\ s > \lambda \\ \dfrac{s}{\lambda} & if\ |s| \le \lambda \\ -1 & if\ s < -\lambda \end{cases} \qquad (11)$$

λ : is a small positive constant represent the width of boundary layer.

C. The speed estimator

The advantage of SMFO is the unrelatedly with rotor speed and when it needed it can be estimated easily as follow:

$$\hat{\omega}_m = \hat{\omega}_s - \hat{\omega}_{sl} = \frac{1}{\psi_r^2}\left(\frac{d\hat{\psi}_{r\beta}}{dt}\hat{\psi}_{r\alpha} - \frac{d\hat{\psi}_{r\alpha}}{dt}\hat{\psi}_{r\beta}\right) - \frac{R_s \hat{T}_e}{p\psi_r^2} \qquad (12)$$

However the computation of the rotor flux derivative is sensitive to noise, so in practice and in order to be useable in the control algorithm the estimated speed has to be filtered by using LPF.

IV. Simulation Results

The control scheme is simulated by using Matlab/Simulink software. Simulation results were obtained for a three-phase *1.1kW* squirrel-cage induction motor with characteristics given in Table. I.

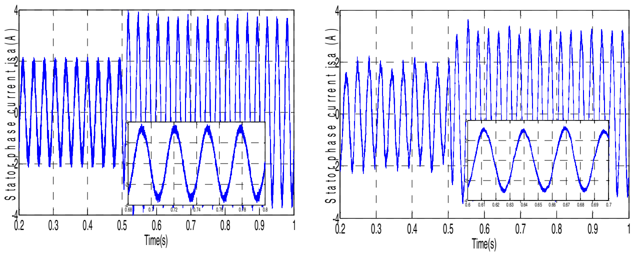
Table I. Induction motor parameters

P=1.1kW	p=2
R_s=6.75 Ω	R_r=6.21Ω
L_s=0.5192 H	J=0.01240 kg.m²
L_r=0.5192 H	f=0.002
M_{sr}=0.4957 H	V=400 V/230V

The results of sensorless control scheme (SVM-DTC) with sliding mode observer are shown in two phases, firstly: SVM-DTC based on load angle control scheme performance analysis compared with conventional DTC, secondly: sliding mode observer performances analysis.

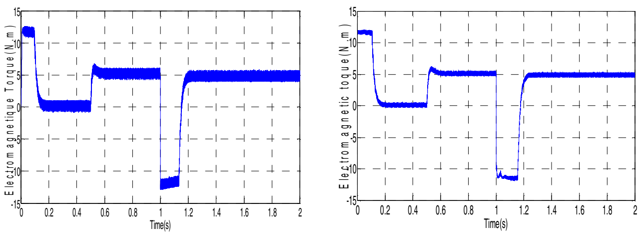
A. Comparative analysis of classical DTC and SVM-DTC

The following figures illustrated comparative study between two sensorless schemes using the proposed SMO, conventional DTC and SVM-DTC, where: the Fig.4.5.6.7 show respectively, stator phase current i_{sa}, electromagnetic torque, stator flux magnitude, stator flux components. (a) For conventional DTC, and (b) for SVM-DTC.



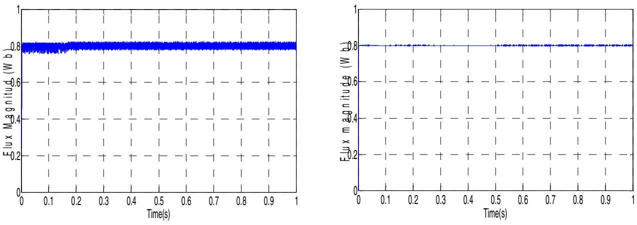
(a) (b)

Fig.4. Stator phase current i_{sa}(A)



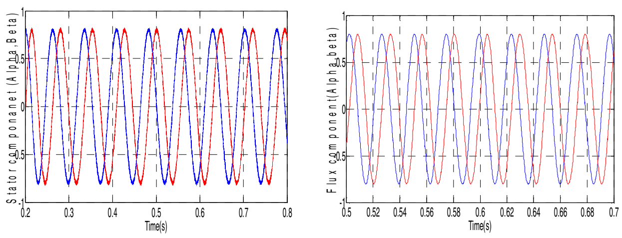
(a) (b)

Fig.5. Electromagnetic torque (Load *5N.m)*



(a) (b)

Fig.6. Flux magnitude (Wb)



(a) (b)

Fig.7. Flux components (Wb).

Fig.4 shows the sinusoid waveform of stator phase current i_{sa} with load of *5N.m* at *0.5s*. The estimated torque in Fig.5 for both conventional and SVM-DTC, it's clear that the torque has good response at the startup and while speed inversion operation, these figures also show the reduced ripples level in current and torque of SVM-DTC strategy compared with conventional DTC.

By comparing simulation results of conventional DTC in Fig.6(a) with those obtained with SVM-DTC in Fig..6(b) it can be seen that the flux ripples for SVM-DTC are considerably reduced.

B. SMO performance analysis

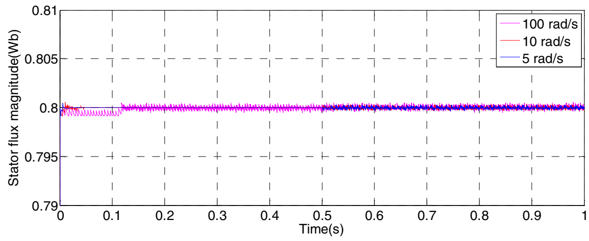


Fig.8. Observed flux magnitude in different speed values (Wb)

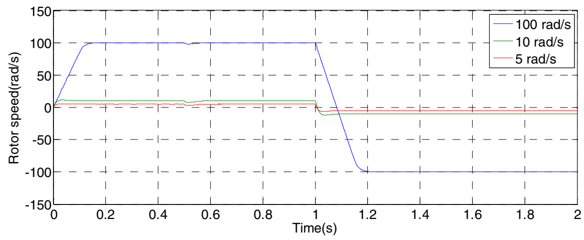


Fig.9. Estimated speed with different references values.

The observed flux is shown in previous test Fig.6 (b).7(b) and in Fig.8 with different speed values, the observation is accurate and consistent at different speeds where the estimation error converges to zero between ± *0.001 Wb*. The speed test is operated with different references from *100 rad/s* to -100 *rad/s* at *t=1s* and in low speeds region from (*10,-10 rad/s*) and (*5,-5rad/s*) with load introduction *5.N.m* at *0.5s*.

The estimated speed in equation (12) follows its references, the estimator is robust against the sense reverse and has good accuracy in different speed values, the speed estimation has no influence on the inherently SMO, it mostly depends on the noise level and filtering operation.

V. EXPERIMENTAL RESULTS

The proposed control scheme, illustrated in previous sections has been implemented in the Matlab/Simulink software and the results were verified by the experimental tests in the laboratory equipped with the real time interface (RTI) associated to the dSpace DS 1104. The implementation platform of induction motor drive is essentially composed as shown in Fig.10 of:

A squirrel-cage IM *1.1 kW*, power electronics Semikron converter composed of a rectifier and an IGBT inverter, speed sensor (dynamo tachymeter), however it was not used in sensorless algorithm, magnetic powder break, dSpace DS 1104 with control desk software plugged in personnel computer, the stator current are measured by Hall type sensors. For reduce the cost of IM drive control system the phase voltage sensors are eliminated, the phase voltages can be estimated from DC-bus voltage and inverter switching states (S_a, S_b, S_c) [13]. A GW-

INSTEK oscilloscope used for obtaining results. The IM parameters are illustrated in Table.I.

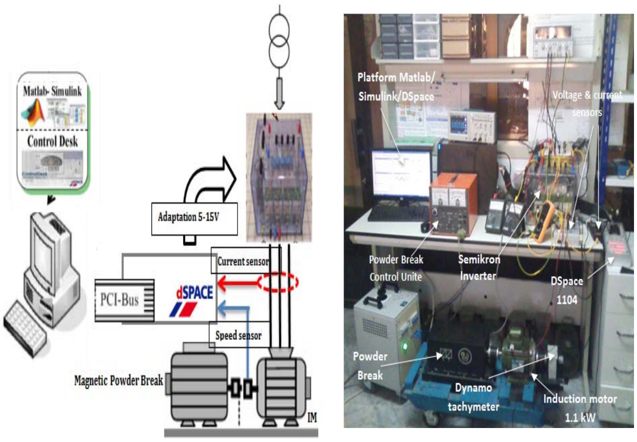


Fig.10. Experimental setup

The experimental results obtained of SVM-DTC with stator flux reference *0.8 Wb* are shown from Fig.11 to Fig.17, the figures from Fig.11 to Fig.13 illustrate respectively: stator phase current, stator flux magnitude and angle flux axes. The Fig.14 and 15 show the load application with speed and current, Fig.16 shows speed sense inversion and finally the Fig.17 shows low speed test at *200 rpm (≈21rad/s)*.

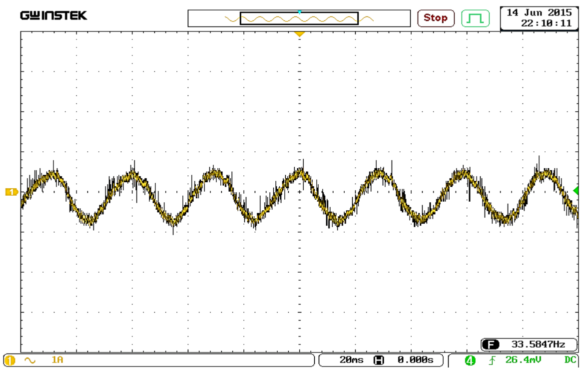


Fig.11. stator phase current

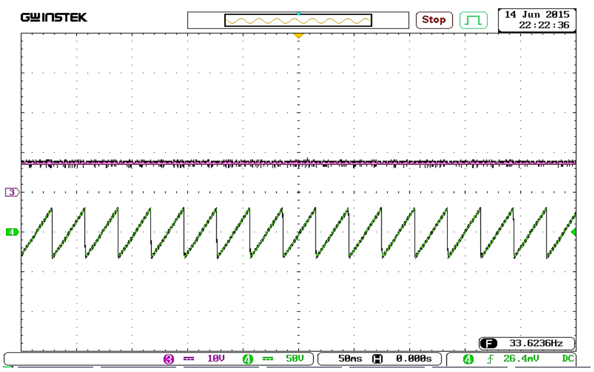


Fig.12. Flux magnitude, flux angle

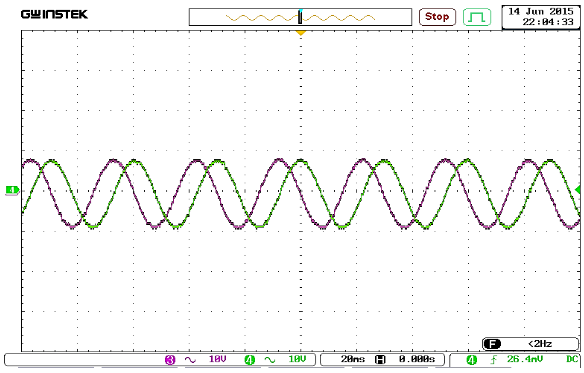


Fig.13. stator flux components in (α,β) axes

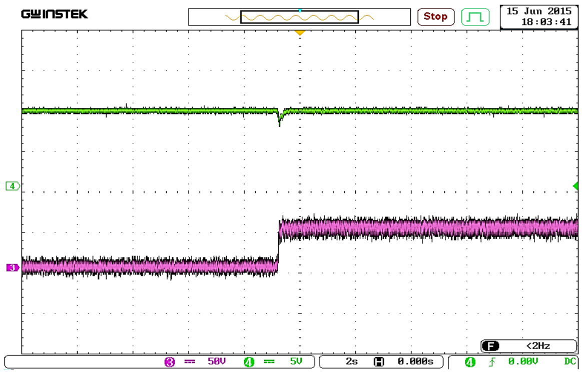


Fig.14. Speed and Torque with load application (5N.m)

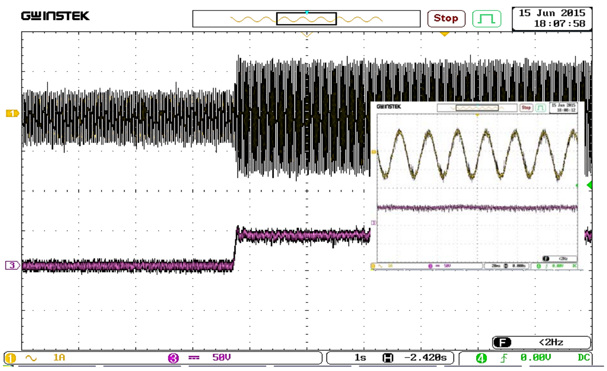


Fig.15 Stator phase current and Torque with load application.

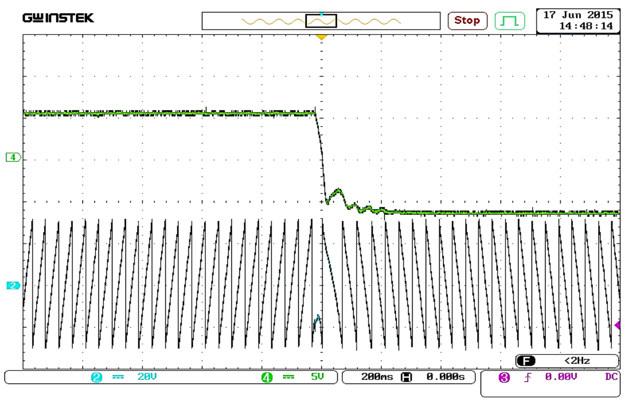


Fig.16. Speed sense reverse, flux angle

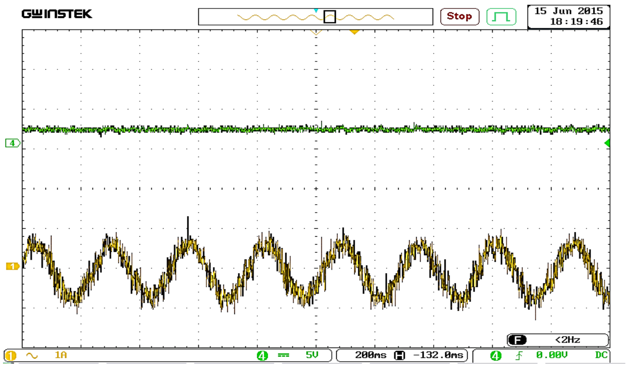


Fig.17. Low speed 200 rpm .

Firstly, Fig.11 shows the stator current (*1div=1A*) at high speed region (*1000 rpm*) and without load it can be noted the good sinusoids waveform. Fig.12 shows the flux magnitude which follows its reference value *0.8 Wb* (*1div=1Wb*) with flux angle (*1div=2rad*). Stator flux components in (α,β) axes are shown in Fig 13, we can notice also the good waveform.

The Fig.14, 15 show the introduction of load torque *5N.m,* the Fig. 14 from the top illustrates: rotor speed *1000 rpm* (*1div=500rpm*), estimated torque (*1div=5N.m*), the next one Fig.15: stator current with estimated torque. In these figures, the low ripple level of torque is noted because of the use of SVM-DTC algorithm, the torque follows the load value while the speed rejects the disturbance quickly and the current responds to load's application. The next test is the speed sense reverse (*600rpm,−600rpm*) Fig.16, the figure illustrates from the top rotor speed (*1div=500rpm*) , flux angle (*1div=5rad*) , it can be noted the sense reverse of speed, angle, which was so rapid and indicates the quick response of DTC. The last test in Fig.17 is low speed region *200 rpm (≈21rad/s)*, we can notice a good response and good current's ripple level with transient state while reference variation.

Generally the proposed sensorless control scheme associated with SMO has a considerably low ripple level in torque and flux cause of the use of space vector modulation, fast response, robustness and good estimation accuracy in different tests, different speed regions, speed sense reveres and load application, with good current waveform.

VI. Conclusion

In this paper, we present a modified sensorless control strategy composed of SVM-DTC method based on load angle, in order to reduce flux, torque and current ripple's level and get fast dynamic with good response in low speed region. In addition an inherently sliding mode flux observer does not require the speed's adaptation mechanism. The proposed strategy using SVM has many advantages verified experimentally using dSpace platform, as: reduced torque and flux ripples, good response during low speed operation, simple control with only one PI torque controller, good waveforms of stator current, and constant switching frequency. In the other hand, the effectiveness and performances of SMO have also been verified. They show good accuracy and acceptable errors level in both speed and flux estimation, robustness in different tests as load application, sense reverse, low speed operation.

Therefore DTC-SVM is a good solution in general to overcome the drawbacks of classical DTC. The coupling with sensorless algorithm can get more high performances for induction motor electrical drive.

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