A Comparative Study between DTC, SVM-DTC and SVM-DTC with PI Controller of Induction Motor

IDIR Abdelhakim[(1)], KIDOUCHE Madjid[(1)], ZELMAT Mimoune[(1)] and AHRICHE Aimad [(1)]

[(1)] *Département de la maintenance industrielle, Faculté des sciences de l'ingénieur,*
Université M'Hamed Bougara de Boumerdès,
Avenue de l'Indépendance, 35000, Boumerdès, Algeria,
E-Mail: idir_ah@yahoo.fr

Abstract— **Direct Torque Control is a control technique in AC drive systems to obtain high performance torque control. The conventional DTC drive contains a pair of hysteresis comparators. DTC drives utilizing hysteresis comparators suffer from high torque ripple and variable switching frequency. The most common solution to those problems is to use the space vector depends on the reference torque and flux.**
In this paper a comparison is made between DTC, SVM-DTC and SVM-DTC with PI controller. The results of the Matlab- Simulink simulations with different algorithms without hysteresis band has been compared. The performances of the three control schemes are evaluated in terms of torque and current ripples.

Key-Words— Induction Motor, Direct Torque Control, Torque ripple, Space Vector Modulation

NOMENCLATURE

P	Number of pole pairs.
I_{sd}, I_{sq}	Stator currents in $d-q$ frame (reference fixed frame).
$\varphi_{sd}, \varphi_{sq}$	Stator fluxes in $d-q$ frame (reference fixed frame).
φ_s^*	Reference flux
T_e	Electromagnetic torque
T_e^*	Reference torque
V_{sd}, V_{sq}	Stator voltages in $d-q$ frame (reference fixed frame).
V_{sd}^*, V_{qd}^*	Reference voltages in $d-q$ frame (reference fixed frame).
$K_{P\varphi}, K_{I\varphi}$	proportional and integration constant of stator flux
K_{PT}, K_{IT}	Proportional and integration constant of torque

I. INTRODUCTION

IN the middle of 80s new strategies for the torque of induction motor was presented by I. Takahashi and T. Noguchi as Direct Torque Control (DTC) [97] and by M. Depenbrock as Direct Self Control (DSC) [1, 2, 3]. Those methods thanks to the other approach to control of IM have become alternatives for the classical vector control– FOC. The authors of the new control strategies proposed to replace motor decoupling and linearization via coordinate transformation, like in FOC, by hysteresis controllers, which corresponds very well to on-off operation of the inverter semiconductor power devices. These methods are referred to as classical DTC. Since 1985 they have been continuously developed and improved by many researchers.

Simple structure and very good dynamic behavior are main features of DTC.

However, classical DTC has several disadvantages, from which most important is variable switching frequency.

Recently, from the classical DTC methods a new control techniques called Direct Torque Control – Space Vector Modulated (DTC-SVM) has been developed.

In this new method disadvantages of the classical DTC are eliminated. Basically, the DTC-SVM strategies are the methods, which operates with constant switching frequency. The DTC-SVM structures are based on the same fundamentals and analysis of the drive as classical DTC. Presented DTC-SVM technique has also simple structure and provide dynamic behavior comparable with classical DTC. However, DTC-SVM method is characterized by much better parameters in steady state operation.

In this paper three different DTC schemes will be compared with each other. These three schemes are Classical DTC with switching table, DTC-SVM method and DTC-SVM with PI controller. The Proposed scheme is described clearly and simulation results are reported to demonstrate its effectiveness.

The entire control scheme is implemented with Matlab/Simulink.

II. DIRECT TORQUE CONTROL SCHEMES

A. Classical DTC Scheme

The fundamental idea of DTC is to control both the torque and the magnitude of flux within the associated error bands in real time. In order to understand DTC principle some of the equations of the Induction motor need to be reviewed. The electromagnetic torque can be expressed as a

function of the stator flux and the rotor flux space vectors as follows:

$$Te = \frac{3P}{4}(\varphi_{sd}I_{sq} - \varphi_{sq}I_{sd}) \tag{1}$$

Considering the modulus of rotor and stator fluxes constant, torque can be controlled by changing the relative angle between both flux vectors. Stator flux can be adjusted by stator voltage equation in stator fixed coordinates:

$$V_{sd} = R_s I_{sd} + \frac{d\varphi_{sd}}{dt} \tag{2}$$

The inverter switching states are selected according to the errors of the torque and flux which are indicated by:

$$\begin{cases} \Delta T_e = T_e^* - T_e \\ \Delta \varphi_s = \varphi_s^* - \varphi_s \end{cases} \tag{3}$$

Where
T_e^*: Reference torque
φ_s^*: Reference flux

$$\varphi_s = \sqrt{\varphi_{sd}^2 + \varphi_{sq}^2} \tag{4}$$

And position of the stator flux

$$\theta_e = tan^{-1}\left[\frac{\varphi_{sq}}{\varphi_{sd}}\right] \tag{5}$$

This means that the change in the stator flux vector is determined by the applied voltage vector. If a voltage vector is applied that changes the stator flux to increase the phase angle between the stator flux and rotor flux vectors, then the torque produced will increase.
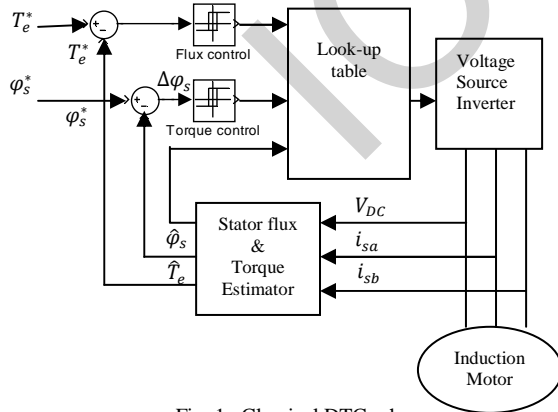The generic and or classical DTC scheme for a VSI-fed Induction Motor was developed a shown in Fig. 1.

Fig. 1. Classical DTC scheme

As it can be seen, there are two different loops related to the magnitudes of the stator flux modulus and torque. The reference values for the stator flux modulus and the torque are compared with the estimated values.

B. The SVM-DTC

Direct flux and torque control with space vector modulation (DTC-SVM) schemes are proposed in order to improve the classical DTC. The DTC-SVM strategies operate at a constant switching frequency. In the control structures, space vector modulation (SVM) algorithm is used. The type of DTC-SVM strategy depends on the applied flux and torque control algorithm. Basically, the controllers calculate the required stator voltage vector and then it is realized by space vector modulation technique.

A three phase two level converters provides eight possible switching states made up six active and two zero switching states. SVM Switching rules of Vs should be a circle, only one switching per state transition; not more than three switching is one Ts. The final state of one sample must be the initial state of the next sample, this rules help in limiting the number of switching actions and there is a reduction in the switching losses and the lower THD (total harmonic distortion). The direct controlled variables are the motor voltage and motor frequency Flexibility to select in active states and their distribution in switching time period gives two degrees of freedom [4, 5, 6].

C. The SVM-DTC with PI Controller

In this scheme there are two proportional integral (PI) type controllers instead of hysteresis band regulate the torque and the magnitude of flux. As shown in Fig. 2, two proportional integral (PI) type controllers regulate the flux amplitude and the torque, respectively. Therefore, both the torque and the magnitude of flux are under control, thereby generating the voltage command for inverter control. Noting that no decoupling mechanism is required as the flux magnitude and the torque can be regulated by the PI controllers. Due to the structure of the inverter, the DC bus voltage is fixed, therefore the speed of voltage space vectors are not controllable, but we can adjust the speed by means of inserting the zero voltage vectors to control the electromagnetic torque generated by the induction motor. The selection of vectors is also changed. It is not based on the region of the flux linkage, but on the error vector between the expected and the estimated flux linkage vectors [7].
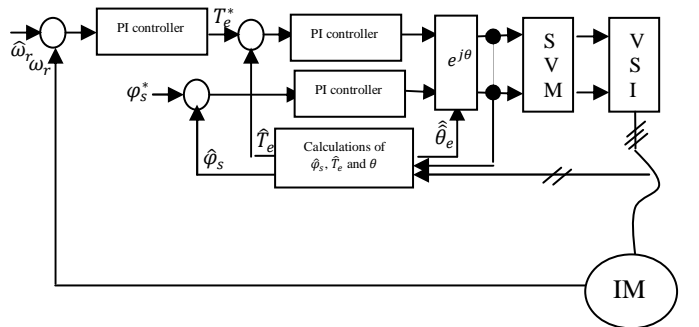

Fig. 2 DTC-SVM with PI scheme

The d-q components of the reference voltage vector in a stator flux reference frame are:

$$\begin{cases} V_{sd}^* = (K_{P\varphi} + K_{I\varphi}) * \Delta\varphi_s \\ V_{sq}^* = (K_{PT} + K_{IT}) * \Delta T_e \end{cases} \quad (6)$$

Where

$\Delta\varphi_s = \varphi_s^* - \hat{\varphi}_s$ and $\Delta T_e = T_e^* - \hat{T}_e$

$$\begin{cases} V_{sd} = R_s I_{sd} + \dfrac{d}{dt}(\varphi_s)) \\ V_{sq} = R_s I_{sq} + \omega_S \varphi_S \end{cases} \quad (7)$$

$$\omega_s = \dfrac{d}{dt}\theta_e$$

where

θ_e: Stator flux vector angle

$K_{P\varphi}, K_{I\varphi}$: Proportional and integration constant of stator flux

K_{PT}, K_{IT}: Proportional and integration constant of torque

The electromagnetic torque can be expressed by the following formula:

$$T_e = 1{,}5 P \varphi_s I_{sq} \quad (8)$$

The transfer function of PI controllers is given as follows:

$$G_r(s) = K_P + \dfrac{K_I}{s} \quad (9)$$

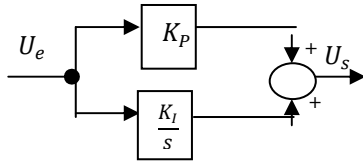The PI controller scheme is presented in Fig. 3.

Fig. 3 Block diagram of PI controller

Presented above model of the controller was used in DTC-SVM control method with two PI controllers.

The SVM unit produces the inverter control signals. It receives the reference voltages in a stator flux reference frame. The SVM principle is based on the switching between two adjacent active vectors and a zero vector during one switching period.

III. SIMULATION RESULTS

To show the effectiveness of the DTC-SVM with PI controller a simulation work has been carried out on induction motor. The proposed scheme is simulated with Matlab/Simulink. Fig. 4 and Fig. 5 shows the simulation results. Fig. 4(a) shows the torque response for Classical DTC. Fig. 4(b) shows the torque response with the DTC-SVM scheme. Fig. 4(c) shows the torque response with the DTC-SVM with PI controller.

A comparison between results obtained show that SVM-DTC with PI strategy reduced ripples for the torque by 60% when compared with classical DTC and by 30% when compared with SVM-DTC.
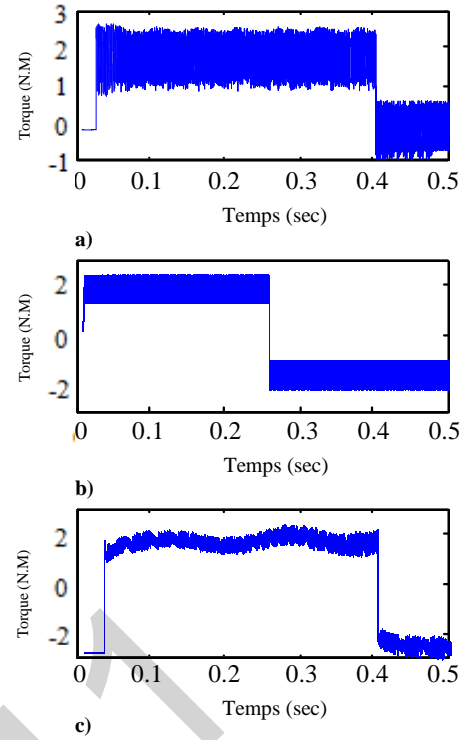

Fig. 4 Torque Response: a) Classical DTC, b) DTC-SVM, c) DTC-SVM with PI

This results show that the torque ripple in the three-level scheme has been reduced significantly.

Fig. 5(a) shows the Stator flux loci for Classical DTC. Fig. 5(b) shows the Stator flux loci with the DTC-SVM scheme. Fig. 5(c) shows the Stator flux loci with the DTC-SVM with PI controller.
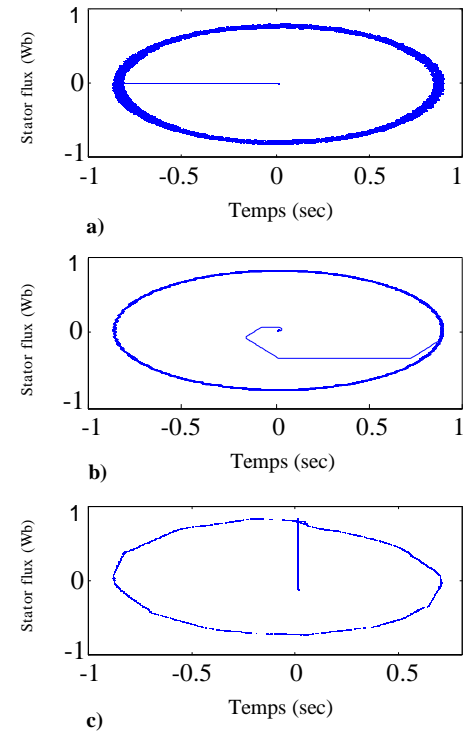

Fig. 5 Stator flux loci: a) Classical DTC, b) DTC-SVM, c) DTC-SVM with PI

These results give a good agreement, that torque variations through the transient period in the case of SVM-DTC with PI controller has lower ripple when compared with that obtained in the other two cases. The stator current variations through the transient period in the case of the SVM-DTC with PI controller has lower over shoot, lower ripple and has reached steady state faster when compared with that obtained in the other two cases.

IV. CONCLUSION

This paper presents a comparative study between the conventional direct torque control, the SVM-DTC, and the SVM-DTC with PI controller. Control methods have been simulated by using control system design based on MATLAB software. The simulation results obtained for the DTC-SVM with PI controller illustrate a considerable reduction in torque ripple and flux ripple compared to the existing classical DTC system and DTC-SVM.

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