Performances Assessment of Direct Torque Controlled IM Drives Using Fuzzy Logic Control and Space Vector Modulation Strategy

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***Abstract*—**This paper deals with the direct torque control (DTC) of the induction motor. This type of control allows decoupling control between the flux and the torque without the need for a transformation of coordinates. However, as with other hysteresis-based systems, the classical DTC scheme represents a high ripple, in both the electromagnetic torque and the stator flux and a distortion in the stator current. As well, it suffers from variable switching frequency. To solve these problems various modifications, in conventional DTC scheme, have been made during the last decade.

Indeed the DTC based on space vector modulation (SVM) has proved to generate very low ripples in torque and flux with constant switching frequency. It also shows almost the same dynamic performances as the classical DTC system. On the other hand, fuzzy logic is considered as an interesting alternative approach for its advantages: Analysis close to the exigencies of user, ability of nonlinear systems control, best dynamic performances and inherent quality of robustness.

Therefore, two fuzzy direct torque control approaches, for the induction motor fed by SVM-voltage source inverter, are proposed in this paper. By using these two approaches of DTC, the advantages of fuzzy logic control, space vector modulation, and direct torque control method are combined. The performances of these DTC schemes are evaluated through digital simulation using Matlab/Simulink platform and fuzzy logic tools. Simulation results illustrate the effectiveness and the superiority of the proposed Fuzzy DTC-SVM schemes in comparison to the classical DTC.

***Keywords*—**Direct torque control, Fuzzy logic control, Induction motor, Switching frequency, Space vector modulation, Torque and flux ripples.

I. Introduction

IN high performance applications of induction motor such as motion control, it is usually desirable that the motor can provide good dynamic response of torque as it is obtained in the dc motor drive. Several control schemes have been proposed for this goal [1]-[4], [15]-[18]. In recent years, an innovative control method, called direct torque control has been introduced due to its capability to produce a fast torque control for the induction motor without to use much on-line computation as in field-oriented-control. Classical DTC uses two hysteresis controllers for the stator flux and developed torque, respectively. Though that the DTC has high dynamic performances, it has few drawbacks such as high ripples, in the torque, flux, and current and also the variation in switching frequency of the inverter [1], [3]-[18]. To overcome these problems a variety of techniques, different in concept, are described in literatures. Some of the diversity of the proposed solutions include DTC with SVM [1], [3]-[8], different power converter topologies such as the multi-level inverters [9]-[11], matrix converter [10], [12], sensorless methods [9], [14], optimum estimator of stator flux for high speed operation [15], [17], and artificial intelligence techniques such as fuzzy and neuro controllers [5], [12]-[18].

As objective to solve problems of the ripples in the torque and the flux and the inconstant switching frequency of the inverter, we have proposed and studied in this work, two approaches of DTC scheme making use of both the technique of space vector modulation (SVM) and the fuzzy logic control. Indeed fuzzy control is a way for controlling a system without the need of knowing its mathematic model [12]-[18]. Also the space vector pulse width modulation (SVM) uses a numerical algorithm to obtain an appropriate sequence of the inverter switching and to generate an output voltage vector approaching to the best, the reference voltage vector with a beforehand imposed switching frequency [1]-[8].

In the first approach of Fuzzy DTC-SVM, called DTFC, the fuzzy logic control is introduced with the aim of reducing the ripples of the stator flux and the electromagnetic torque and improving the shape of the stator currents. The angle of the reference voltage vector is chosen through a look-up table, and a fuzzy logic estimator is proposed to calculate the amplitude of the reference voltage vector, leading to an optimal control for both torque and flux to their required values [13], [15]. In the second approach of Fuzzy DTC-SVM (FDTC-SVM), the two fuzzy logic controllers generate the reference voltage vector. The use of fuzzy controllers permits a faster response and more robustness. As an intelligence method, the fuzzy control does not need the accurate mathematic model of the process to be controlled, and uses the experience of user's knowledge to form its control rule bases [14], [18].

The performances of these two modified DTC approaches are demonstrated by simulation using Matlab/Simulink software and fuzzy logic tools. Simulation results have been compared to those of classical DTC scheme.

II. Model of Induction Motor

The dynamic behavior of an induction machine is described by the following equations written, in terms of space vectors in a stationary reference frame [2]-[17]:

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$$\vec{V_s} = R_s.\vec{\imath_s} + \frac{d\vec{\emptyset_s}}{dt} \quad (1)$$

$$\vec{V_r} = 0 = R_r.\vec{\imath_r} + \frac{d\vec{\emptyset_r}}{dt} - j\omega.\overrightarrow{\emptyset_s} \quad (2)$$

$$\vec{\emptyset_s} = L_s.\vec{\imath_s} + L_m.\vec{\imath_r} \quad (3)$$

$$\vec{\emptyset_r} = L_r.\vec{\imath_r} + L_m.\vec{\imath_s} \quad (4)$$

where R_s and R_r: represent the stator and rotor resistances, L_s, L_r and L_m: designate the self and mutual inductances, and ω: signify the electrical rotor speed.

The electromagnetic torque is expressed in terms of stator and rotor fluxes as: (with P is the pole pair number)

$$\Gamma_e = P\frac{L_m}{\sigma L_s L_r}(\vec{\emptyset_s}.j\vec{\emptyset_r}) \quad (5)$$

The elimination of $\vec{\imath_s}$ and $\vec{\imath_r}$ from (1) to (4) gives the equations of induction machine in the state variable form with, the stator flux, and the rotor flux, as state variables:

$$\begin{bmatrix} \frac{d\vec{\emptyset_s}}{dt} \\ \frac{d\vec{\emptyset_r}}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{\sigma T_s} & \frac{L_m}{\sigma T_s L_r} \\ \frac{L_m}{\sigma T_r L_s} & j\omega - \frac{1}{\sigma T_r} \end{bmatrix} \cdot \begin{bmatrix} \vec{\emptyset_s} \\ \vec{\emptyset_r} \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} . \vec{V_s} \quad (6)$$

with $T_s = \frac{L_s}{R_s}$, $T_r = \frac{L_r}{R_r}$ and $\sigma = 1 - \frac{L_m^2}{L_s.L_r}$.

The mechanical mode associated to the rotor motion, is described by:

$$J\frac{d\Omega}{dt} = \Gamma_e - \Gamma_r(\Omega) \quad (7)$$

where $\Gamma_r(\Omega)$ and Γ_e are respectively the load torque and the electromagnetic torque developed by the machine.

III. Principle of Classical Direct Torque Control

The basic model of the conventional DTC-IM scheme is shown in Fig. 1. The performances of the system depend directly on the estimation of the stator flux, and the torque [1], [3], [6], [8]-[18]. Flux estimation is based on the stator voltage expression, where the components of, stator current ($i_{s\alpha}$, $i_{s\beta}$), and voltage ($v_{s\alpha}$, $v_{s\beta}$) are obtained by the following equations:

$$\begin{cases} i_{s\alpha} = \sqrt{\frac{2}{3}} i_{sa} \\ i_{s\beta} = \frac{1}{\sqrt{2}}(i_{sb} - i_{sc}) \end{cases} \quad (8)$$

$$\begin{cases} v_{s\alpha} = \sqrt{\frac{2}{3}} V_{dc}(S_a - (S_b + S_c)/2) \\ v_{s\beta} = \frac{1}{\sqrt{2}} V_{dc}(S_b - S_c) \end{cases} \quad (9)$$

where S_a, S_b *and* S_c are the switching states of the upper devices of a classical two-level inverter (see Fig. 2 (a))

The estimated stator flux is then given by:

$$\begin{cases} \hat{\emptyset}_{s\alpha} = \int_0^t (v_{s\alpha} - R_s i_{s\alpha})\, dt \\ \hat{\emptyset}_{s\beta} = \int_0^t (v_{s\beta} - R_s i_{s\beta})\, dt \end{cases} \quad (10)$$

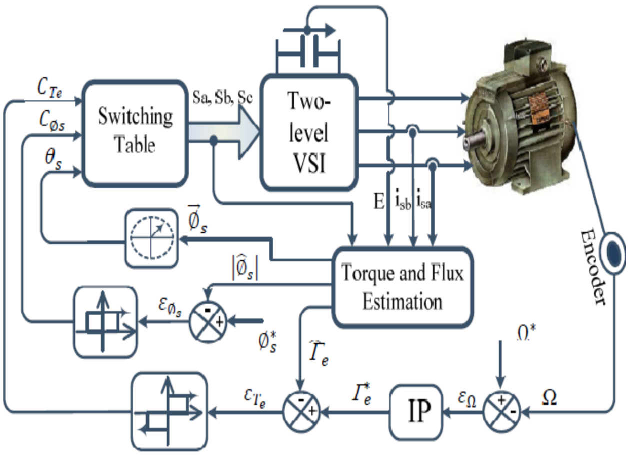

Fig. 1 Block diagram of the classical DTC

The electromagnetic torque is estimated as follow:

$$\hat{\Gamma}_e = P(\hat{\emptyset}_{s\alpha} i_{s\beta} - \hat{\emptyset}_{s\beta} i_{s\alpha}) \quad (11)$$

Otherwise the electromagnetic torque can be expressed as a function of space vectors of the stator flux and the rotor flux:

$$\Gamma_e = P\frac{L_m}{L_s L_r - L_m^2} \emptyset_s \emptyset_r sin(\gamma_s - \gamma_r) \quad (12)$$

According to (1) and if the voltage drop in the stator resistance is neglected, the variation of the stator flux is directly proportional to the applied stator voltage:

$$\vec{v_s} \approx \frac{d\vec{\emptyset_s}}{dt} \text{ or } \vec{v_s} \approx \frac{\Delta\vec{\emptyset_s}}{\Delta t} \quad (13)$$

Because the rotor time constant is larger than the stator one, the rotor flux slowly changes compared to the stator flux. Thus, torque can be controlled by quickly varying the stator flux position by means of the applied stator voltage as shown in Fig. 2 (b). The tangential component (*y*) of the stator voltage will affect the relative angle, between the two vectors of stator flux and rotor flux, and in turns will control the torque variation according to (12). The radial component (*x*) will control the amplitude of the stator flux vector.

As it can be seen in Fig. 1, there are two different loops corresponding to the electromagnetic torque and the stator flux modulus. The reference values for the torque and the modulus of stator flux are compared with the estimated values. The resulting error values are fed into two hysteresis blocks of two-level and three-level respectively. The outputs of these two hysteresis blocks, together with the position of the stator flux are used as the inputs to the famous look up table of Takahashi [3]-[11], [14]-[18].

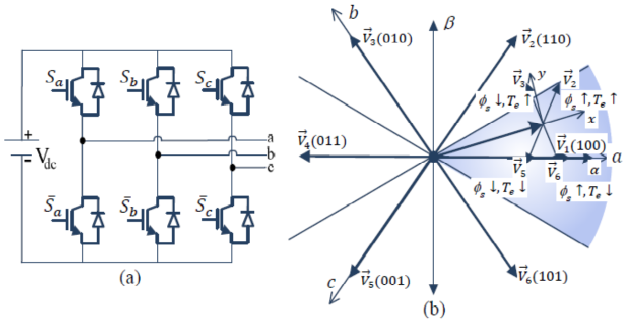

Fig. 2 (a) Schematic diagram of a two-level-VSI
(b) Control of stator flux and torque by means of voltage vectors

IV. Space Vector Modulation Strategy

Space vector modulation technique was published two years earlier than DTC and is one of the most widely utilized strategies to generate sinusoidal line-to-line voltages. It has several advantages such as; better DC bus utilization, lower torque ripples, lower Total Harmonic Distortion (THD) in the AC motor current, and lower switching losses. Besides, it is well suited to digital implementation [1]-[8], [14]-[18].

The principle of SVM is based on the concept of approximating a rotating reference voltage vector $\vec{V}_s^*$ using a combination of two out of the eight possible vectors that can be generated from a three-phase inverter [1]-[7]. The eight state vectors of the two level inverter can be expressed as follows:

$$\begin{cases} \vec{V}_k = \sqrt{\frac{2}{3}} V_{dc} e^{j(k-1)\frac{\pi}{3}} \\ \vec{V}_{k+1} = \sqrt{\frac{2}{3}} V_{dc} e^{jk\frac{\pi}{3}} \\ \vec{V}_0 = \vec{V}_7 = 0 \end{cases} \quad (14)$$

The SVM strategy differs from the modulations with carrier waves, in such way that there are not separate modulators used for each of the three phases. Instead, the complex reference voltage vector is processed as a whole. It is well known that the SVM is produced by the regular-sampling of a circular locus of a reference voltage in the two-axis plan. These voltage samples are then represented by two actives vectors, chosen from $\vec{V}_1$ to $\vec{V}_6$, adjacent to the reference voltage sample together with either the two null vectors; $\vec{V}_0$ and $\vec{V}_7$ by adjusting their respective times within a sampling time [1]-[8], [16]-[18].

Fig. 3 (a) shows the principle; where the reference vector $\vec{V}_s^*$ is sampled at fixed and equal intervals of time $'T_s'$, called 'sub-cycle'. The sampled value $V_s^*(t_s)$ is then used to solve the following equations:

$$\begin{cases} T_k.\vec{V}_k + T_{k+1}.\vec{V}_{k+1} = T_s.V_s^*(t_s) \\ T_0 = T_s - T_k - T_{k+1} = T_7 \end{cases} \quad (15)$$

where $\vec{V}_k$ and $\vec{V}_{k+1}$ are the two switching state vectors adjacent in space, to the reference vector $\vec{V}_s^*$, Fig. 3 (b). The solutions of (14) and (15) are in order, the on-durations T_k, T_{k+1}, and T_0 of the switching state vectors $\vec{V}_k, \vec{V}_{k+1}, \vec{V}_0$:

$$\begin{cases} T_k = \left(\cos\left[(k-1)\frac{\pi}{3}\right] V_{s\alpha}^* + \sin\left[(k-1)\frac{\pi}{3}\right] V_{s\beta}^*\right) \frac{T_s}{V_{dc}} \\ T_{k+1} = \left(\cos\left[(k+1)\frac{\pi}{3}\right] V_{s\alpha}^* + \sin\left[(k+1)\frac{\pi}{3}\right] V_{s\beta}^*\right) \frac{T_s}{V_{dc}} \\ T_0 = T_s - T_k - T_{k+1} = T_7 \end{cases} \quad (16)$$

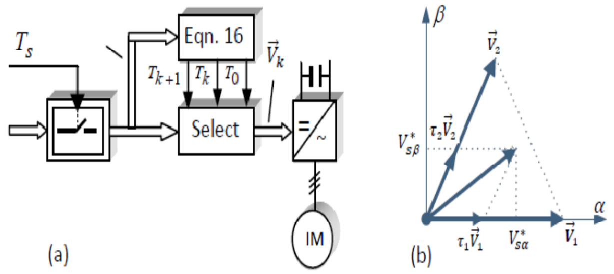

Fig. 3 Space vector modulation; (a) Bloc diagram, (b) Switching state vectors of the first 60°-sector

If the over-modulation mode $(T_k + T_{k+1} > T_s)$ occurs, the time duration should be scaled as (17) to generate the best approximate of the desired voltage vector. This may be detected by examining the sign of the calculated $'T_0'$, and the limit is applied by maintaining the angle of the voltage vector:

$$\begin{cases} T_k' = T_k.\frac{T_s}{T_k+T_{k+1}} \\ T_{k+1}' = T_{k+1}.\frac{T_s}{T_k+T_{k+1}} \\ T_0' = 0 \end{cases} \quad (17)$$

Having computed these on-durations, an adequate sequence (in time) of the switching state vectors must be determined. The modulation scheme used in this work is based on a symmetrical sequence within each sampling period. Under this scheme, the switching sequence in a given sector can be described as follow:

$$\vec{V}_{0 \text{ or } 7} \Rightarrow \vec{V}_k \Rightarrow \vec{V}_{k+1} \Rightarrow \vec{V}_{0 \text{ or } 7} \Rightarrow \vec{V}_{k+1} \Rightarrow \vec{V}_k \Rightarrow \vec{V}_{0 \text{ or } 7}$$

This sequence is characterized by reduced switching losses and a lowest harmonic distortion due to the symmetry in the switching of the inverter devices.

V. Direct Torque Fuzzy Control (DTFC)

The direct torque fuzzy control scheme (DTFC) proposed in this work employs the space vector modulation. The corresponding scheme is given in Fig. 4. Here the errors of flux and torque are used as the inputs, to the fuzzy logic estimator of the amplitude of the reference voltage vector (V_s^*) and to the hysteresis comparators, which deliver the level of errors ($C_{Te}, C_{\phi s}$) used by the look-up-table of the voltage vector angle.

Unlike the conventional DTC scheme, where the voltage vector applied has a constant amplitude even if the position of the torque is outside his hysteresis band, the DTFC scheme allows the calculation of the optimum voltage to be applied to the machine, according to the position of stator flux and torque relative to their required values. Thus, provides a fast and accurate control of the electromagnetic torque. The voltage vector is then synthesized using space vector modulation. As a result, the SVM technique generates switching states of the inverter [13]-[16].

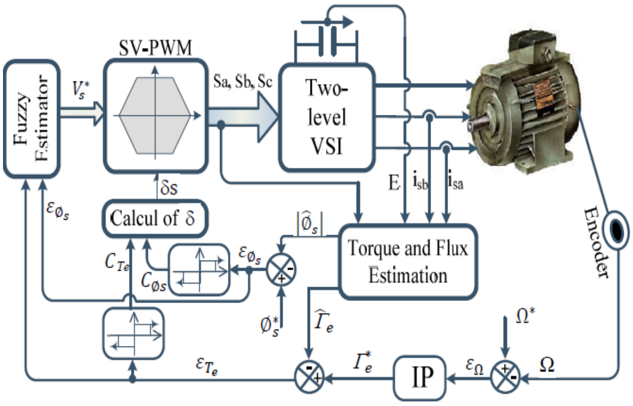

Fig. 4 Block diagram of the proposed DTFC scheme

A. Selection of the Voltage Vector Position

The position of the voltage vector $\vec{V}_s^*$, relative to the stator flux vector θ_s must be chosen to maintain the stator flux and the electromagnetic torque in an optimal error band around their reference values. Indeed, the reference voltage position δ_s is obtained by adding an angle δ, to the position of the stator flux. This angle is selected based on the values of hysteresis comparators output (Table I) such as:

$$\delta_s = \delta + \theta_s \tag{18}$$

It should be noted here, that hysteresis comparators of the torque and the flux are both, regulators of three levels.

TABLE I
LOOK-UP TABLE OF VOLTAGE VECTOR ANGLE

C_{Te}	-1			0			1		
$C_{\emptyset s}$	-1	0	1	-1	0	1	-1	0	1
δ	$-\frac{2\pi}{3}$	$+\pi$	$+\frac{2\pi}{3}$	$-\frac{\pi}{2}$	$+\frac{\pi}{2}$	$+\frac{\pi}{2}$	$-\frac{\pi}{3}$	0	$+\frac{\pi}{3}$

B. Selection of the Voltage Vector Amplitude

The amplitude of voltage vector must be chosen so as to reduce the errors of flux and torque. A fuzzy logic estimator is designed to generate appropriate voltage vector amplitude. The bloc diagram of the proposed estimator is given in Fig. 5.

The inference engine bloc, based on the input fuzzy variables uses forty nine (49) 'if then' rules, where the And method corresponds to the minimum fuzzy inputs, in order to obtain the final output fuzzy sets as shown in Table II. These rules have been set to take the maximal amplitude of voltage vector when the torque is outside its error band. Otherwise, zero amplitude is assigned.

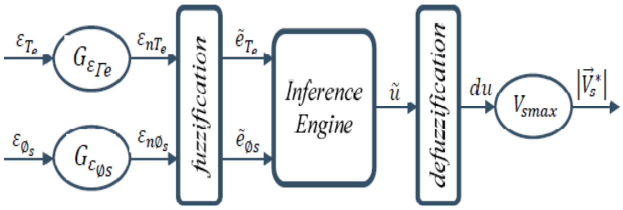

Fig. 5 Proposed fuzzy estimator for the amplitude of voltage vector

The defuzzification bloc uses the gravity centre technique to transform the fuzzy set to a crisp output. The amplitude of voltage vector is then obtained by multiplying the crisp output value (du) by an appropriate weight. The output weight is chosen so that the maximum voltage vector amplitude should not exceed the maximum amplitude of a voltage vector generated by the two-level PWM inverter [13]-[18].

TABLE II
RULES BASE FOR VOLTAGE AMPLITUDE ESTIMATOR

$\tilde{e}_{\emptyset s}$ \ $\tilde{e}_{Te}$	NH	NM	NS	ZE	PS	PM	PH
NH	PH	PM	PS	PS	PS	PM	PH
NM	PH	PM	PS	PS	PS	PM	PH
NS	PH	PM	PS	ZE	PS	PM	PH
ZE	PH	PM	PS	ZE	PS	PM	PH
PS	PH	PM	PS	ZE	PS	PM	PH
PM	PH	PM	PS	PS	PS	PM	PH
PH	PH	PM	PS	PS	PS	PM	PH

NH: negative high, **NM**: negative medium, **NS**: negative small, **ZE**: zero, **PS**: positive small, **PM**: positive medium, **PH**: positive high

VI. DTC-SVM USING FUZZY LOGIC CONTROLLERS

A. Approach Description

The principle of the second approach of Fuzzy DTC-SVM (FDTC-SVM) is similar to classical DTC. The difference is using fuzzy logical controllers to replace the hysteresis regulators of torque and flux, as shown in Fig. 6.

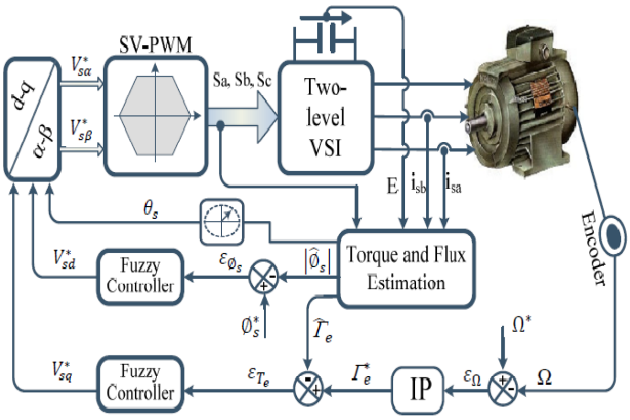

Fig. 6 Block diagram of the proposed FDTC-SVM

B. Design of Flux &Torque Fuzzy Logic Controllers (FLC)

Fuzzy logic control is the process of formulating the mapping from a given input to an output using fuzzy logic. It has some advantages such as it does not need any exact mathematical method. As shown in Fig. 7, a classical fuzzy logic control consists of three parts: fuzzification process, linguistic rule base, and defuzzification process. Input variables are the error between commanding value and real value of the flux or the torque and their derivative [14]-[18].

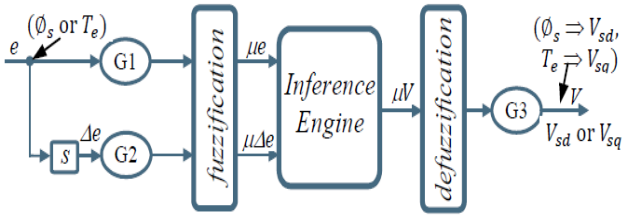

Fig. 7 Basic structure of fuzzy logic controller

The fuzzification and defuzzification processes are carried out using asymmetrical triangular membership functions. Fig. 8 presents the membership functions of the input and the output of FLC that are used for both control of the torque and the flux. Although the same FLC is employed for both the torque and flux, it should be considered that the normalizing gains are different in each controller [13]-[16].

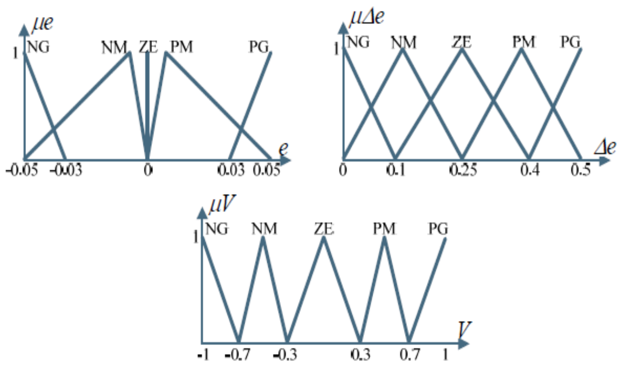

Fig. 8 Fuzzy membership functions for variables of inputs and output

The fuzzy inference is accomplished through the linguistic rules. These rules are the most important part of the controller and they define the type of the used control. Proper design of the rules leads to desired performance of the control system [13]-[18]. Table III represent the linguistic rules base that introduces a PI-type FLC. The outputs of fuzzy logic controllers of flux and torque are used as the reference components of the stator voltage which are delivered to SVM stage.

TABLE III
FUZZY RULES FOR COMPUTATION OF V_{sd} OR V_{sq}

e \ Δe	NH	NM	ZE	PM	PH
NH	NH	NH	NH	NM	ZE
NM	NH	NH	NM	ZE	PM
ZE	NH	NM	ZE	PM	PH
PM	NM	ZE	PM	PH	PH
PH	ZE	PM	PH	PH	PH

VII. SIMULATION RESULTS AND INTERPRETATION

A computer simulation was performed for the two proposed Fuzzy DTC-SVM schemes, to evaluate their performances using the software package of Matlab/Simulink and fuzzy logic tools. The used induction motor parameters in these simulations are listed in the Appendix.

To show the effectiveness of the two Fuzzy DTC-SVM schemes, the performances are compared with those of the classical DTC. The simulation results included in Fig. 9, for several operating conditions, show that high dynamic performances can still be achieved even in the responses of speed, torque, flux and current with no distinct difference among the three DTC schemes.

A comparison of steady-state behaviors obtained using the three DTC schemes is given in Figs. 10 and 11, where for all, the machine is running at high speed (100 rad/s) with, full load (20 Nm). From obtained results, we can see that the two Fuzzy DTC-SVM schemes illustrate better performances by reducing the ripples in torque and stator flux.

For the same steady-state operating conditions, we can observe significantly in Fig. 11, that the harmonic content of the stator current is highly reduced by employing mainly the FDTC-SVM wherein the stator line voltage has been found more close to the suitable staircase signal.

From the stator flux locus given in Fig. 12, we can notice that an appreciable reduction at the level of ripple of stator flux is obtained with both proposed DTC schemes. Mainly by using the second approach of Fuzzy DTC-SVM, the flux trajectory represents the lowest ripples in steady-state.

By representing the inverter switching frequency in Fig. 13, we have demonstrated that use of SVM strategy in the proposed fuzzy DTC schemes gives to the switching frequency of the inverter, a constant average value for the various, speed or torque commands (according to Fig. 9).

VIII. CONCLUSION

In this paper, two fuzzy direct torque control schemes based on space vector modulation, are thoroughly analyzed, studied and implemented on Matlab/Simulink platform and fuzzy logic tools.

Through the different simulations, the two Fuzzy-DTC-SVM schemes have shown their effectiveness and their superiority to the conventional DTC, without deteriorating the capability of the dynamic control of this technique. The most important improvements are:

- Reduction of ripples in the torque and the stator flux for transient and steady-state responses.
- Attenuated distortions in the, stator voltage and the current waveforms,
- Constant switching frequency for all operating conditions (thanks to apply SVM),

Lower inverter switching frequency is obtained with the use of FDTC-SVM (in comparison to the DFTC). Which may reduce switching losses as well as stress on semiconductor switches of the inverter.

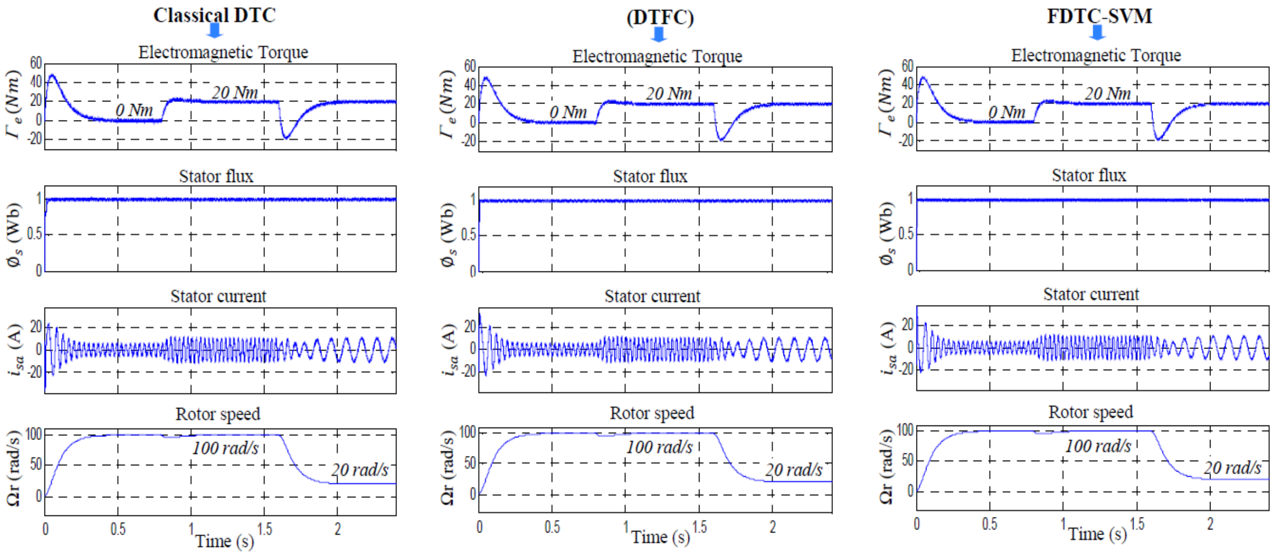

Fig. 9 System responses for various operating conditions with the three DTC schemes

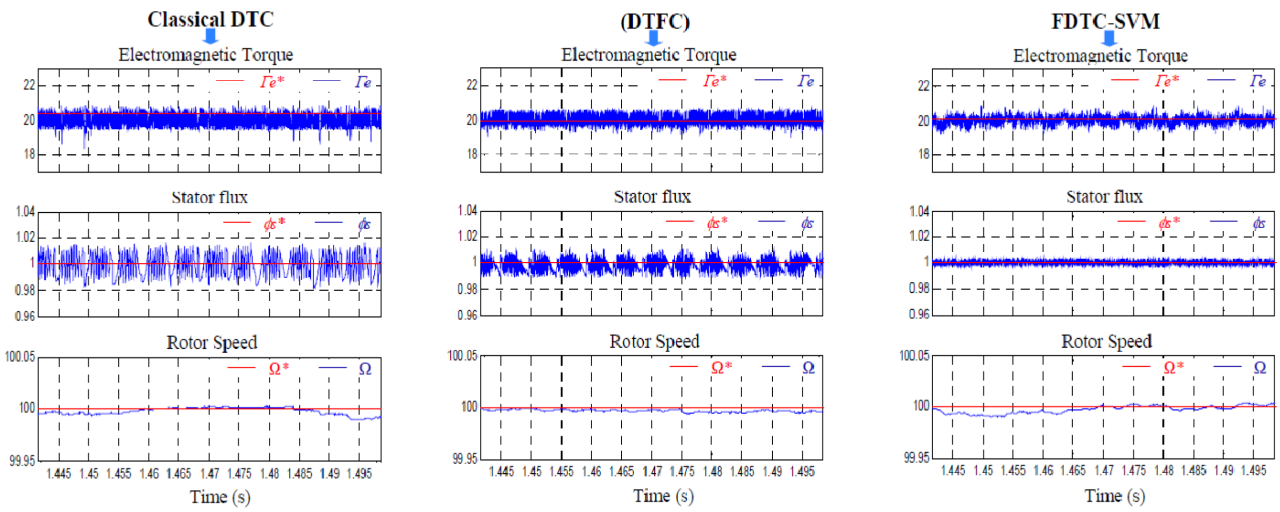

Fig. 10 Steady-state responses, of torque, flux, and speed with the three DTC schemes

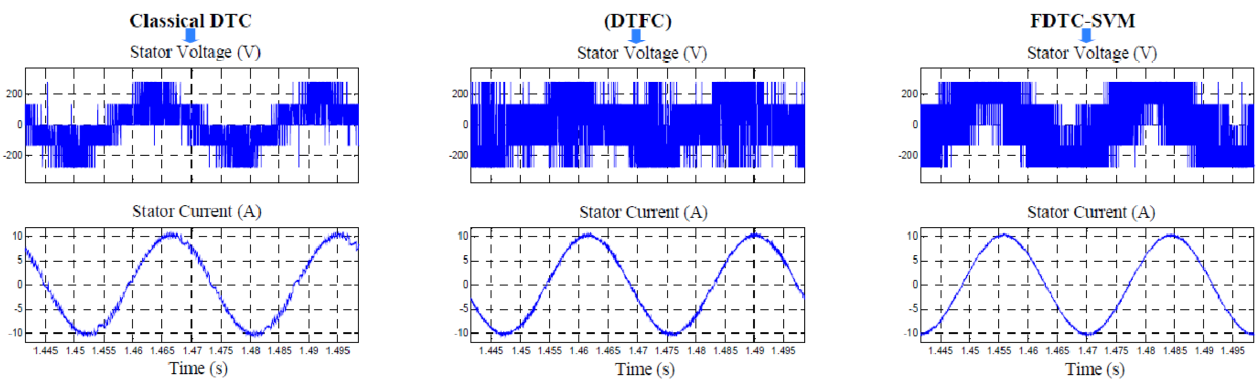

Fig. 11 Steady state responses of the stator voltage and the stator current under the three DTC schemes

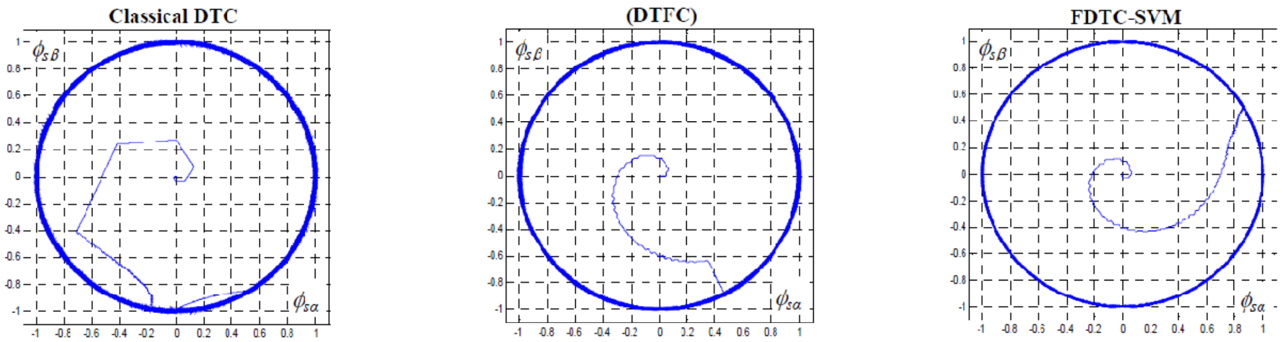

Fig. 12 Locus of stator flux under the three DTC schemes

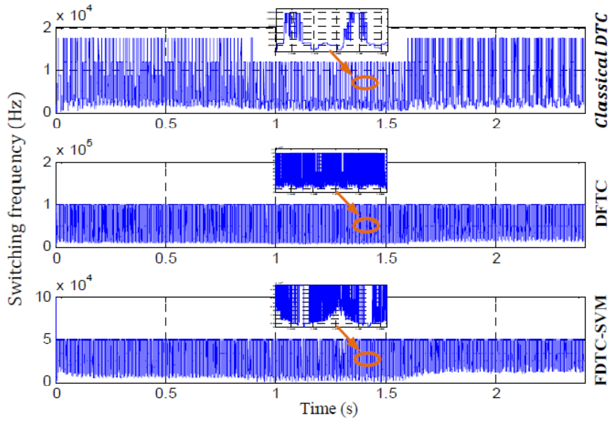

Fig. 13 Inverter switching frequency under the three DTC schemes

APPENDIX

TABLE IV
INDUCTION MOTOR PARAMETERS

Parameters	Values
Power / Stator Voltage (Kw -V)	4 / 220
Stator / Rotor resistance (Ω)	1.2 / 1.8
Stator / Rotor leakage inductance (H)	0.1554 / 0.1568
Mutual inductance / Number of poles (H -)	0.15 / 2
Inertia / Friction coefficient (Nm/rd/s - Kg.m^2)	0.07 / 0.0001

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