Comparison by Simulation of Various Strategies of Three Level Induction Motor Torque Control Schemes for Electrical Vehicle Application

L. YOUB, A. CRACIUNESCU

Abstract — **In this paper three new direct torque control strategies are compared with the classical direct torque control for an induction motor feed by a three level inverter. The considered new strategies are: direct torque control strategy with fuzzy logic regulators instead of hysteresis regulators, direct torque control strategy with hysteresis regulators associated with fuzzy logic regulators and direct torque control strategy with fuzzy, hysteresis and space vector modulation. The comparison is based on the simulation results obtained with MATLAB/SIMULINK program.**

Key words— **Induction machine, direct torque control, Fuzzy logic, Space vector modulation, three level inverter**.

I. INTRODUCTION

Many control techniques have been applied on induction motors [1, 2]. Among these techniques, direct torque control (DTC) introduced by Takahashi appears to be very convenient for EV applications [3, 4]. Most of the literature is focused on the application of DTC with two-level inverters. However, DTC with a three level inverter is still a matter of research. The present work is based on the study of the application of DTC with the three-level NPC inverter, and the advantages that can be obtained. When using a three-level inverter the selection of the output voltage vector becomes more complex due to the higher number of available inverter states. For this purpose three different control methods have been designed. The first one is based on the conventional DTC scheme adapted for three-level inverter. The second one is based on a fuzzy logic controller instead of hysteresis regulators for the inverter state selection. And the third one is a DTC strategy with fuzzy, hysteresis and space vector modulation. The required measurements for this control technique are only the voltage and the current measurements. Flux, torque, and current are estimated. The objective of this paper is to analyze the performance of the various DTC strategies on the sole induction motor used for electric vehicle application.

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II. THE DIRECT TORQUE CONTROL ALGORITHM

The DTC algorithm, which is employed with a 3-level inverter, is a natural extension of the classical DTC to multilevel inverters. In this paper, the so-called diode clamped 3-level inverter has been used as shown in Fig.1. With such an inverter, the possible inverter switching states, for each phase, are shown in Tab.I where S_X is a variable that identifies the switching state of an inverter leg. Each voltage space vector generated by the inverter is then identified by a 3-component vector, like (2 2 1), where each component is given by the value of S_X for each of the three legs of the inverter: Fig. 2 shows the hexagon of the 19 voltage space vectors which can be generated by such an inverter. The proposed DTC algorithm employs only 12 active voltage space vectors, divided into two categories on the basis of the parameter Lev_U (voltage level) as shown in Tab.II, without using either the null space vector, for dynamical reasons as will be explained later in this paragraph, or the active vectors (210 102 120 201 021 012), which are characterized by three different numbers, for capacitor balancing reasons, as will be explained later on in §III.

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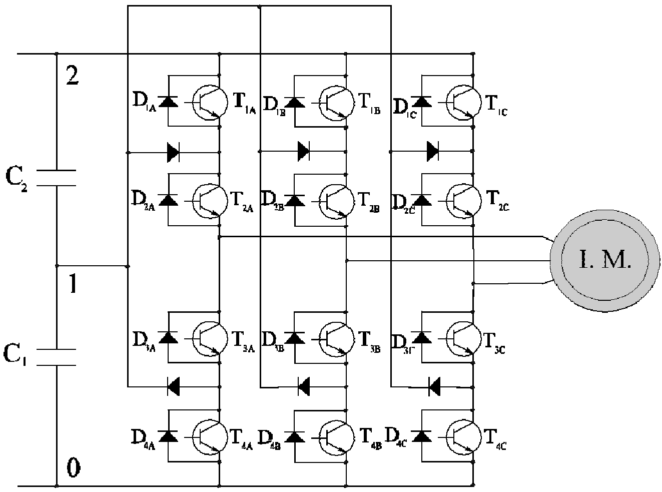

Fig. 1 Schematics of a 3-level diode-clamped inverter

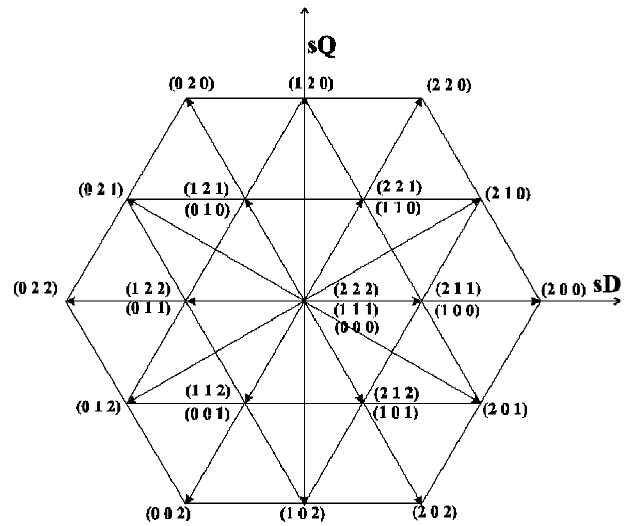

Fig. 2 Hexagon of the voltages of a 3-level inverter

As it can be seen from Tab.II, any u_i space vector (with i=1, 2, …,6) with Lev_U= low can be obtained with two different switching patterns and this is exploited to avoid the capacitor voltage unbalance, as shown in §III.

TABLE. I
SWITCHING STATES OF A 3-LEVEL INVERTER

S_{xA}	S_{1A}	S_{2A}	S_{3A}	S_{4A}
2	On	On	Off	Off
1	Off	On	On	Off
0	Off	Off	On	On

TABLE. II
VOLTAGE SPACE VECTORS EMPLOYED IN THE PROPOSED DTC ALGORITHM

		u_1	u_2	u_3	u_4	u_5	u_6
Lev_U	High	2 0 0	2 2 0	0 2 0	0 2 2	0 0 2	2 0 2
	Low	2 1 1	2 2 1	1 2 1	1 2 2	1 1 2	2 1 2
		1 0 0	1 1 0	0 1 0	0 1 1	0 0 1	1 0 1

The employed DTC block diagram, shown in Fig. 3, is the natural extension of the classical DTC. It shows that the closed-loop control of both the rotor speed and the stator flux linkage is performed. Employing a PI controller that processes the speed error obtained as the difference between the reference speed and the measured speed, which is obtained by the encoder as Fig. 3a, does speed control. The output of the speed controller is used as the reference torque. Both torque and stator flux controls are achieved by using 4-level hysteresis comparators (Fig. 3): the output this comparator (T_{out} for the torque and Ψ_{out} for the stator-flux linkage) can be either 2 (–2) or 1 (–1) according to the positive (negative) value of the torque or the flux error: if the value of the error is within the hysteresis loop, then the output of the comparator is 1 (-1) if the previous comparator output was 1 or 2 (-1 or -2). On the basis of the i (i=1, 2, …,6) in which the stator flux linkage lies and of the magnitude of the errors of the torque and flux loops, a voltage space vector u_i (with i=1, 2, …,6 - see Tab.III) is generated. In this control strategy, no null vector has been used to obtain the best dynamical performances of the electric drive, at the expenses though of higher ripples in the torque. If the absolute value of the output of one of the two the comparators is higher than two, then the voltage space vector u_i with Lev_U=”high” is generated, otherwise u_i with Lev_U=”low” is selected. As clearly it is shown in Fig. 4, the effect of the voltage space vector with Lev_U=”high” is to cause high variations both in the torque and in the stator flux, while the effect of the voltage space vector with Lev_U=”low” is to cause smaller variations. The use of more voltage vectors in the 3-level inverter feed DTC than in the 2-level inverter feed DTC permits therefore a corresponding reduction of the harmonic content in stator voltages and currents.

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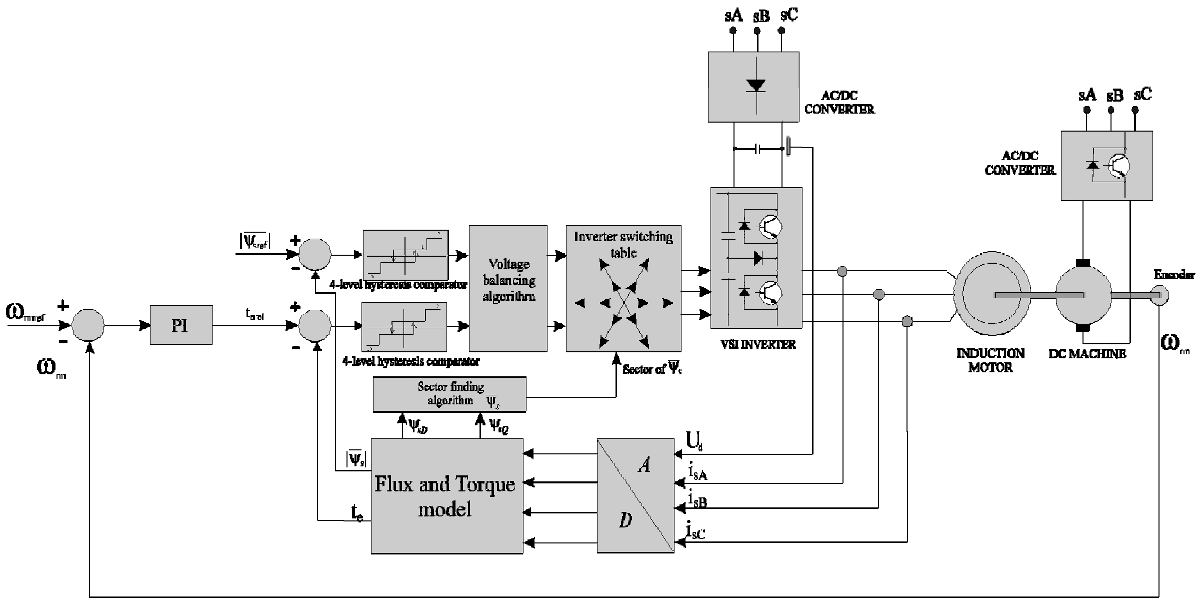

Fig. 3 Block diagram of the DTC drive with a three-level inverter

II. THE FUZZY DIRECT TORQUE CONTROL

In Fig. 4 is shown the block diagram of an induction motor drive system feed by a three-level inverter fuzzy regulators DTC system feed of an induction machine. The three-phase output voltage waveforms are generated by various switching combinations of the switches. The NPC three-level inverter and the induction machine are connected directly, and output transformer or filter is not necessary.

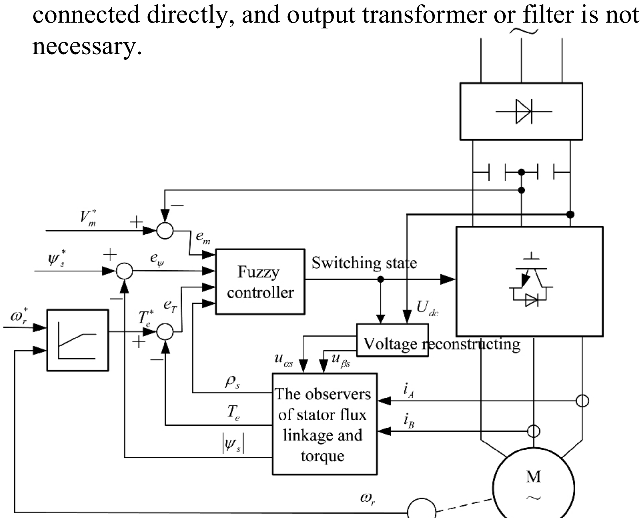

Fig.4 The schematic block diagram of an induction motor feed by a three-level inverter with DTC fuzzy controller and space vector modulation

To get a better control performance a fuzzy logic controller has been introduced to be a compliment to the hysteresis controller. The wide of the hysteresis cycle will be fuzzy variables: b_ϕ for flux controller and b_T for torque controller. The fuzzy controller design is based on intuition and simulation. These values compose a training set which is used to obtain the table of rules. The fuzzy rules' sets are shown in Table 1II. In Fig. 5 it is shown the membership functions of input and output variables and in Fig.6 it is shown the control surface. The rules were formulated using analysis data obtained from the simulation of the system using different values of the torque hysteresis band. The symbols used in Fig. 5 are the following: PH: positive high, NH: negative high, PM: positive medium, NM: negative medium, PS: positive small, NS: negative small, ZE: zero.

The linguistic rules can be expressed by the following example: • If (e1 is NH or NM and e2 is N) then (Δb_Γ or Δb_φ is N):

This case corresponds to a big overshoot in torque error, consequently high torque ripple. To reduce the torque ripple, the value Δb_Γ should be reduced. In this case, the overshoot in torque error can touch the upper band that will cause a reverse voltage vector to be selected. This one will result in a torque rapid decreasing that will determine undershoot in the torque response below the hysteresis band. Therefore, Δb_Γ should not be too small; Δb_Γ is set Positive in order to avoid this situation.

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TABLE III
FUZZY RULES OF TORQUE AND FLUX HYSTERESIS CONTROLLER

e1 / e2 \ Δb_Γ or Δb_φ	NH	NM	NS	ZE	PS	PM	PH
N	N	N	NS	ZE	PS	PS	P
ZE	N	N	NS	ZE	PS	PS	P
P	N	NS	NS	ZE	PS	P	P

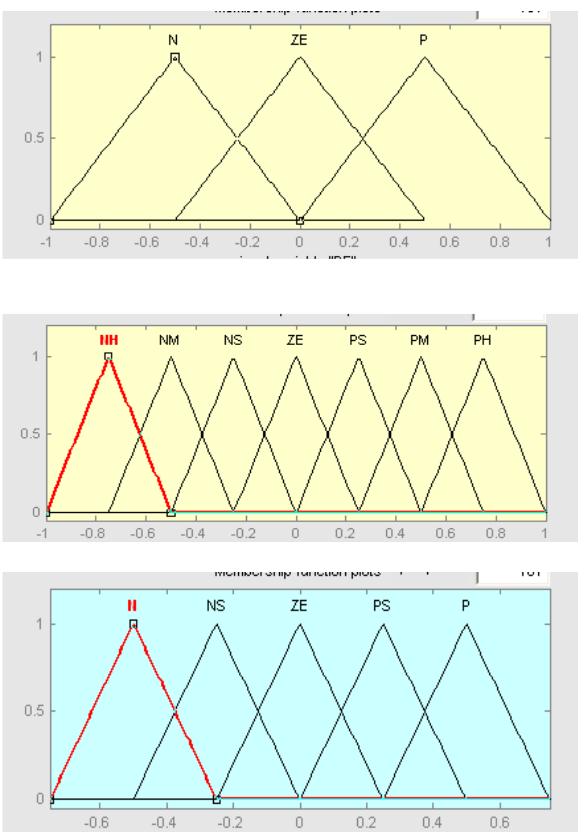

Fig. 5 Input/output variables membership functions

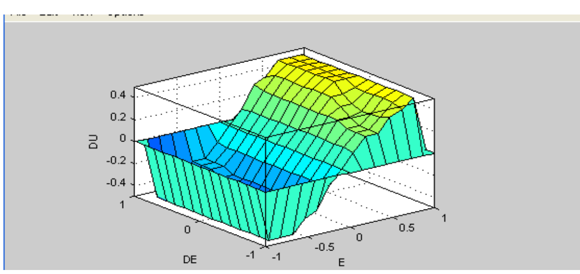

Fig. 6 Control surface

III. SPACE VECTOR MODULATION

The aim of SVM is to minimize harmonic distortion in the current by selecting the appropriate switching vectors and determining their corresponding dwelling widths [5]. As depicted in Fig. 7 there are eight states available for voltage space vector according to eight switching positions of the inverter. SVM is based on time averaging techniques during sampling period T_s. If the reference vector Vs ($V_{ref} = V_1 + V_2$), is located in the sector I (Fig.7), then it is composed of voltage vector $V1$ and $V2$ and zero vectors $V0$ and $V7$ [6]:

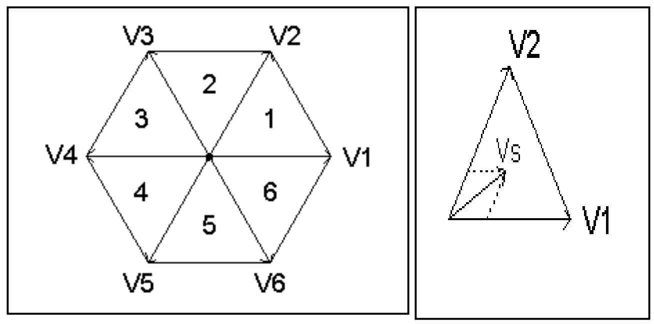

FIG.7. Decomposition of voltage vector

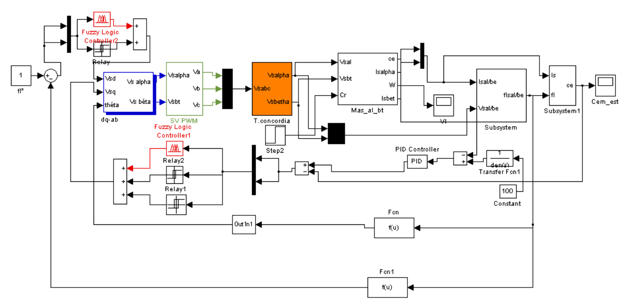

Fig. 8. A novel DTC scheme for ac motor drives with fuzzy hysteresis and space vector modulation

The SVM techniques use the following equations in the process of the synthesis of the reference voltage [6]:

$$T_0 = T_7 = \frac{1}{2}\left(T_s - T_1 - T_2\right) \quad (1)$$

$$T_1 = \frac{T_s}{2}\, a \frac{\sin\left(\pi - \theta\right)}{\sin\left(\frac{\pi}{3}\right)} \quad (2)$$

Several SVM strategies can be used for the piloting of the inverter. The only difference between these strategies is the choice of the null vector and the

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sequence of application of the vector's tension during the period of sampling:

$$T_1 Vs = T_1 V_1 + T_2 V_2 \qquad (3)$$

$$T_1 = \frac{T_s}{2} a \frac{\sin(\theta)}{\sin\left(\frac{\pi}{3}\right)} \qquad (4)$$

where:

$T1$ and $T2$ are the active pulse times of voltage vectors $V1$ and $V2$, and

$$a = \frac{V_s}{\left(\sqrt{\frac{2}{3}} V_{dc}\right)}$$

V_{dc} : d-c link voltage. $T0$, $T7$ are a null vector times.

In Fig.8 is shown the novel DTC scheme for ac motor drives with fuzzy hysteresis and space vector modulation.

IV. SIMULATION RESULTS

The study of the performances of the fuzzy logic controller used with DTC strategy was made by simulation of the system by using MATLAB /SIMULINK and fuzzy logic tools. The problem was to find how to make the flux to rapidly reaching it's given value, when the system is started with direct torque control. In the case of combined control strategy, where the hysteresis regulators are associated with fuzzy regulators and space vector modulation, the used membership functions were the same as in section II. The comparative results obtained by simulation for an induction motor are given in figures (10-12). It is interesting to note that, the torque pulsations in the case of fuzzy DTC with space vector modulation, as it is shown in figure (10), are smaller than in the case of classical DTC with fuzzy Hysteresis, as it is shown in figures 6. But the stator current in this case is bigger. The appropriate figures show the dynamics of the flux and of the torque of the induction motor. The trajectory of stator flux has a reduction of the ripples (figure.12), and trajectory of stator flux is circular. In the case of hysteresis comparators associated with fuzzy regulators one can obtain a fast torque response and good establishment time, as it is shown in figure.11. The simulation results highlighted the superior performances of the combined fuzzy- hysteresis DTC of the induction motor.

In the case of space vector modulation, as we can see from figure 12, the torque ripples are drastically reduced. These results are obtained in spite of using larger sampling period for the DTC with fuzzy associated regulator. The simulation results given in Fig. 12 shows a good tracking of electromagnetic torque using DTC with fuzzy associated regulators and SVM and prove that this technique allows a good dynamic performance similar to the basic DTC schemes. Moreover, it can be noted that the effects due to the crossing of sector boundaries, typical of basic DTC schemes, are avoided when it is used the DTC with hysteresis controller associated with fuzzy regulators scheme.

V. CONCLUSION

In this paper three new DTC strategies are compared with the classical DTC for an induction motor feed by a three level inverter. The analysis was made by numerical simulation. The advantages of the proposed fuzzy direct torque control using space vector modulation technique in comparison with a fuzzy hysteresis of DTC are the following:

– A reduced torque and flux ripples;
– A constant switching frequency due of the SVM presence;
– A fast torque response due of the fuzzy controller contribution;
– A lower sampling time;
– The absence of current and torque ripples caused by sector changes.

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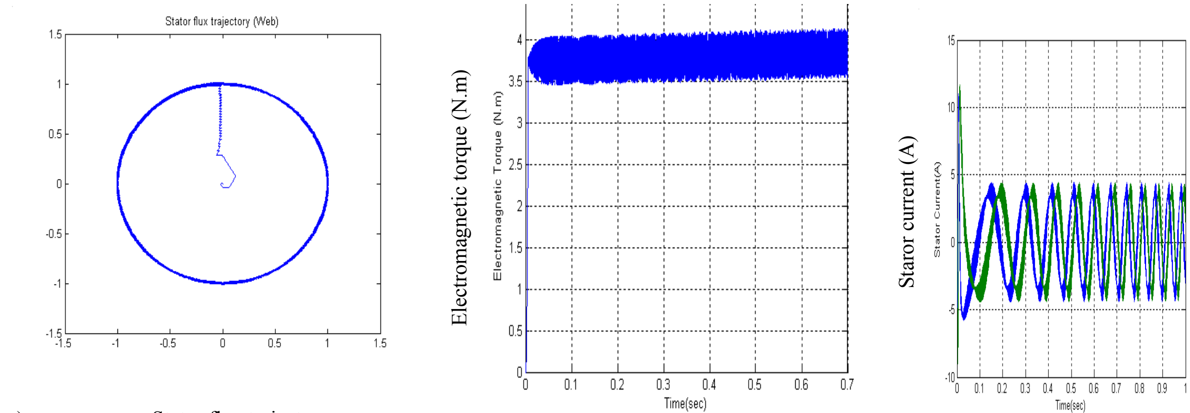
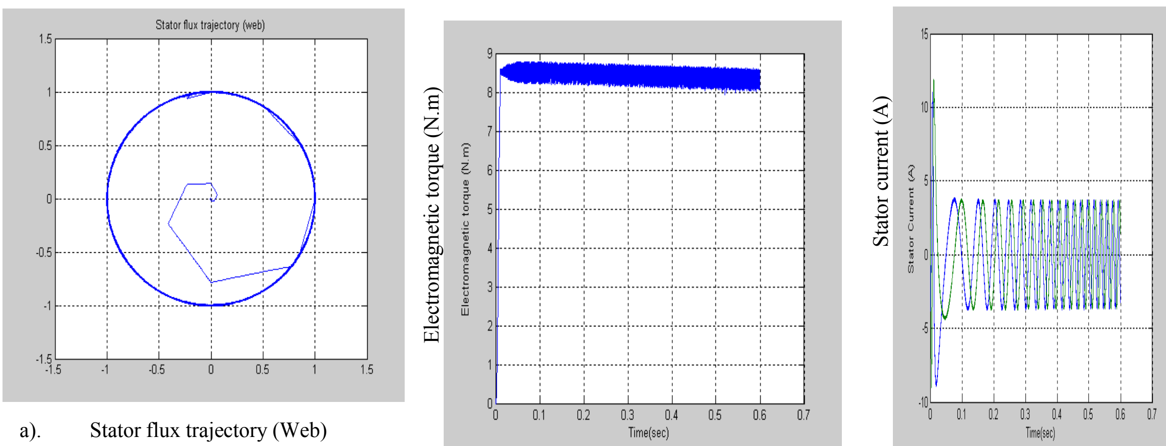


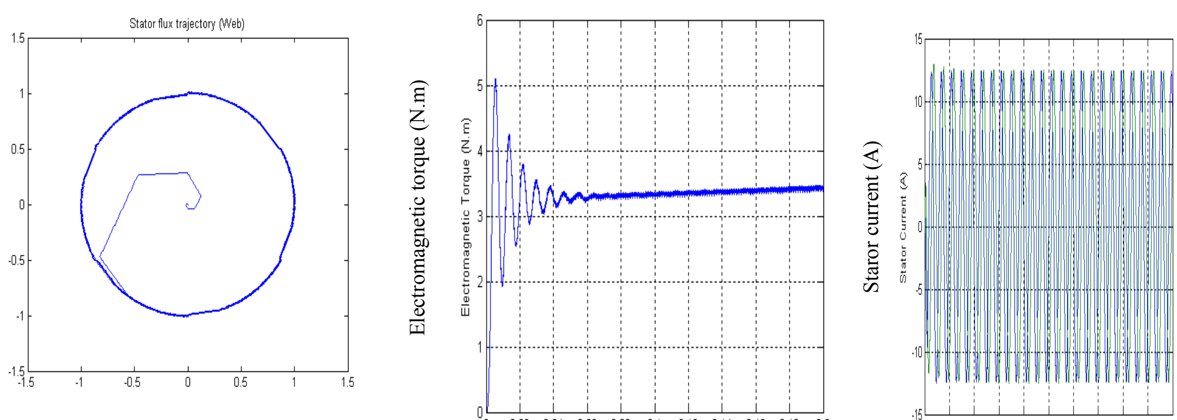
a) Stator flux trajectory
b) Time (sec)
c) Time (sec)

Fig. 10. DTC Conventional with 3-level inverter : a) Stator flux trajectory (Web), b) Electromagnetic Torque (N.m), c) Stator current (A)



a). Stator flux trajectory (Web)
b) Time (sec)
c) Time (sec)

Fig. 11. DTC with fuzzy logic with 3-level inverter a) Stator flux trajectory (Web), b) Electromagnetic Torque (N.m),c) Stator current (A),



a). Stator flux trajectory (Web)
b) Time (sec)
c) Time (sec)

Fig. 12. DTC-SVM with fuzzy logic with 3-level inverter a) Stator flux trajectory (Wb), b) Electromagnetic Torque (N.m),c) Stator current (A).

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