Direct Torque Control of Induction Motor Fed by Three-Level NPC Inverter Using Fuzzy Logic and Neural Network

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Abstract — **multilevel voltage inverter has been receiving wide attention in research and high power applications. Compared with the traditional two-level voltage inverter, the main advantages of the multilevel inverter are a smaller output voltage step, lower harmonic components, a better electromagnetic compatibility and lower switching losses. In this paper direct torque control (DTC) is applied for three-level NPC inverter fed induction machine drives. Two control approaches using Fuzzy DTC, and Neural Network DTC are proposed and compared. The validity of the proposed control scheme is verified by simulation tests of an induction motor drive system. The stator current and voltage, flux, and torque are determined and compared in the above techniques using MATLAB-SIMULINK environment.**

Keywords — DTC, Induction motor, Multi-level inverter, PWM-inverter, Fuzzy logic, Neural Network, Neural-point clamped, Switching algorithm, PI regulator.

I. INTRODUCTION

Multilevel inverters have drawn tremendous interest in the field of high-voltage high-power applications. Its concept is based on producing small output voltage steps, resulting in better power quality. Despite the need for more power transistors, they operate at low voltage levels and also at low switching frequency so that the switching losses are also reduced. Other advantages include better electromagnetic compatibility due to the low dv/dt transitions [1]. Some of the fundamental multilevel topologies include the diode-clamped [2].
Direct Torque Control (DTC) was first introduced by Takahashi in 1986 [3]. The objective of our work is to implement a switching pattern by fuzzy, and neural network that describe the selection strategies of the inverter state exploiting the simplicity of implementation and robustness offered by artificial intelligent control.

II. THE THREE LEVEL NEUTRAL POINT CLAMPED INVERTER

A multilevel voltage source inverter is a converter structure that can provide more than two levels of line to ground voltage in the output of each leg of the inverter.

Multilevel power conversion technology is a very fast growing area of power electronics with good potential for further development. The most attractive features of this technology are in the medium to high-voltage application range (2-13 kV), which include motor drives, power distribution, power quality and power conditioning applications. Different circuit topologies have been implemented in multilevel inverters. One of the most used of these topologies is the Neutral Point Clamped (NPC) topology [2]-[4]. In Fig.1, the scheme for the three-level NPC inverter is presented.
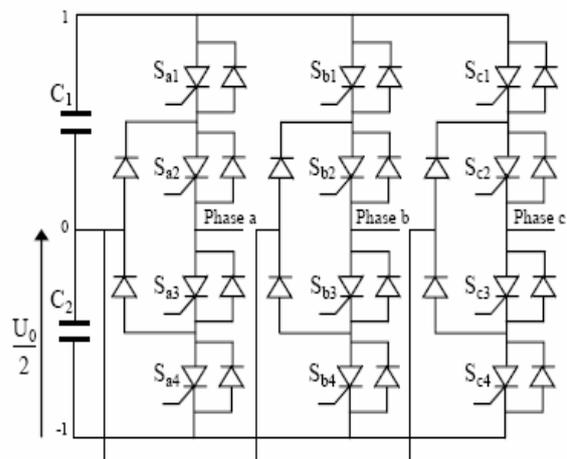
Fig.1. Three-level NPC inverter

In Fig.2, the different vectors or inverter states available, in a three-level inverter, are shown in the stator flux locus. As can be seen, there are 4 different kinds of vectors:
Zero vectors: V0, V7, and V14.
Large vectors: VI5, V16, V17, V18, V19, V20.
Medium vectors: V21, V22, V23, V24, V24, V25, V26.
Small vectors: V1, V2, V3, V4, V5, V6, V8, V9, V10, V11, V12, V13.

Although in a three-level inverter there are 27 possible states, some of them apply the same voltage vector. There are two possible configurations for each small vector and three for the zero vectors. Therefore, 19 different vectors are available in a three-level inverter [5]-[6].
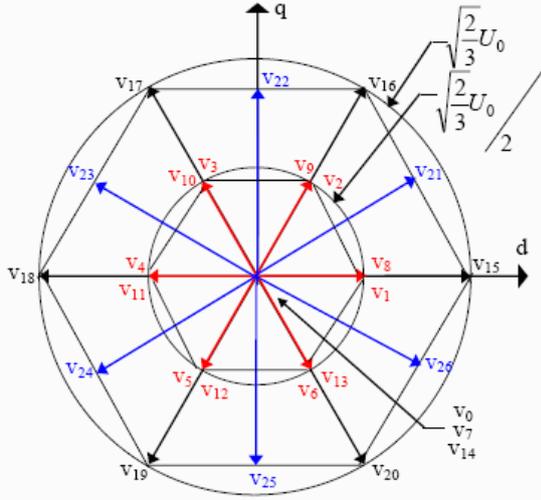
Fig.2. Voltage vectors of a three-level NPC inverter

III. DEVELOPMENT OF TWO DTC APPROACHES

A. Basic DTC

DTC technique is a convenient, relatively complete and easy applicable method. In this method, the required stator flux and torque are determined and a proper switching pattern of the inverter is then applied "Fig.4". Since the motor input voltage contributes in both flux and required torque, a proper switching pattern for inverter firing is essential. In order to define the inverter switching pattern using flux and torque errors, two hysteresis controllers, one for the flux and other for torque are employed [7]-[8] "Fig.3". At any instant, the inverter is switched on using these errors and position of stator flux over twelve-region control in such a way that the inverter output voltage vector minimizes the flux and torque errors and defines the direction of the flux rotation. The outputs of these controllers are S_i (i= a, b, c) where their values (-1, 0 or 1) are used to determine the inverter output voltage vector as follows "Fig.1".

$$v_s = \sqrt{\frac{2}{3}} \cdot \frac{U_0}{2} \cdot \left(S_a + S_b \cdot e^{i\frac{4\pi}{3}} + S_c \cdot e^{i\frac{4\pi}{3}} \right) \quad (1)$$

(i= a, b, c)

$$\begin{cases} S_i = -1 \Rightarrow (S_{i1}, S_{i2}, S_{i3}, S_{i4}) = (0,0,1,1) \\ S_i = 0 \;\; \Rightarrow (S_{i1}, S_{i2}, S_{i3}, S_{i4}) = (0,1,1,0) \\ S_i = 1 \;\; \Rightarrow (S_{i1}, S_{i2}, S_{i3}, S_{i4}) = (1,1,0,0) \end{cases} \quad (2)$$

The control algorithm of this technique can be summarized as follows [9].

$$\begin{cases} if \quad \Delta\varphi > \varepsilon_\varphi & Then \;\; K_\varphi = +1. \\ if \;\; 0 \le \Delta\varphi \le \varepsilon_\varphi \;\; and \; d\Delta\varphi/dt > 0 \; Then \; K_\varphi = 0. \\ if \;\; 0 \le \Delta\varphi \le \varepsilon_\varphi \;\; and \; d\Delta\varphi/dt < 0 \;\; Then \; K_\varphi = +1. \\ if \; -\varepsilon_\varphi \le \Delta\varphi \le 0 \;\; and \; d\Delta\varphi/dt > 0 \; Then \; K_\varphi = -1. \\ if \; -\varepsilon_\varphi \le \Delta\varphi \le 0 \;\; and \; d\Delta\varphi/dt < 0 \;\; Then \; K_\varphi = 0. \\ if \;\; \Delta\varphi < -\varepsilon_\varphi & Then \;\; K_\varphi = -1. \end{cases} \quad (3)$$

$$\begin{cases} if \quad \Delta T > \varepsilon_{T2} & Then \;\; K_T = +11. \\ if \; -\varepsilon_{T1} \le \Delta T \le \varepsilon_{T2} \; and \; d\Delta T/dt > 0 \; Then \; K_T = +1. \\ if \; -\varepsilon_{T1} \le \Delta T \le \varepsilon_{T2} \; and \; d\Delta T/dt < 0 \; Then \; K_T = +11. \\ if \;\; 0 \le \Delta T \le \varepsilon_{T1} \;\; and \; d\Delta T/dt > 0 \; Then \; K_T = 0. \\ if \;\; 0 \le \Delta T \le \varepsilon_{T1} \;\; and \; d\Delta T/dt < 0 \; Then \; K_T = +1. \\ if \; -\varepsilon_{T1} \le \Delta T < 0 \;\; and \; d\Delta T/dt > 0 \; Then \; K_T = -1. \\ if \; -\varepsilon_{T1} \le \Delta T < 0 \;\; and \; d\Delta T/dt < 0 \; Then \; K_T = 0. \\ if \; -\varepsilon_{T2} \le \Delta T \le -\varepsilon_{T1} \;\; and \; d\Delta T/dt > 0 \; Then \; K_T = -11. \\ if \; -\varepsilon_{T2} \le \Delta T \le -\varepsilon_{T1} \; and \; d\Delta T/dt < 0 \; Then \; K_T = -1. \\ if \;\; \Delta T < -\varepsilon_{T2} & Then \;\; K_T = -11. \end{cases} \quad (4)$$

Where ε_{T1}, ε_{T2}, and ε_Φ are the predefined error levels of the torque and flux respectively. Finally, based on the values of constants K_T and K_Φ and the position of the stator (twelve-region control), the inverter switching algorithm is as shown in Tab.1.
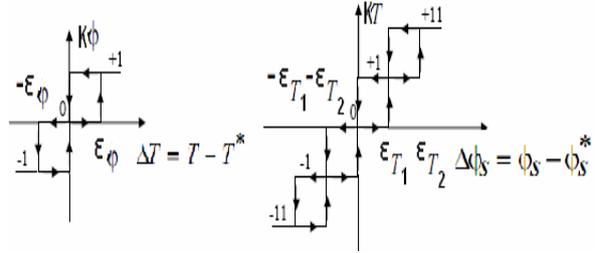
Fig.3. Torque and Flux comparator hysteresis
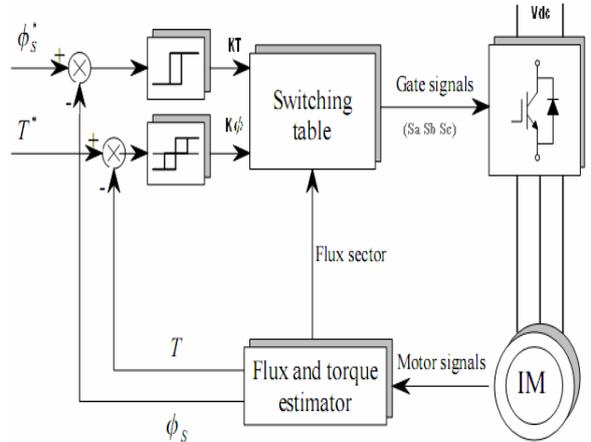
Fig.4. Induction motor direct torque control block diagram (Basic DTC).

The stator flux can be evaluated by integrating from the stator voltage equation:

$$\phi_s = \int (v_s - R_s \cdot i_s) \cdot dt \quad (5)$$

The electromagnetic torque is estimated from the flux and current information as:

$$T = p \cdot (\phi_{ds} \cdot i_{qs} + \phi_{qs} \cdot i_{ds}) \quad (6)$$

The stator flux angle θ_s is calculated by:

$$\theta_s = arctg\left(\frac{\phi_{qs}}{\phi_{ds}}\right) \quad (7)$$

C_φ	C_Γ	S											
		1	2	3	4	5	6	7	8	9	10	11	12
+1	+11	21	16	22	17	23	18	24	19	25	20	26	15
	+1	21	2	22	3	23	4	24	5	25	6	26	1
	0	Zero vector											
	-1	26	1	21	2	22	3	23	4	24	5	25	6
	-11	26	15	21	16	22	17	23	18	24	19	25	20
-1	+11	17	23	18	24	19	25	20	26	15	21	16	22
	+1	3	23	4	24	5	25	6	26	1	21	2	22
	0	Zero vector											
	-1	5	25	6	26	1	21	2	22	3	23	4	24
	-11	19	25	20	26	15	21	16	22	17	23	18	24
0	+11	22	17	23	18	24	19	25	20	26	15	21	16
	+1	22	3	23	4	24	5	25	6	26	1	21	2
	0	Zero vector											
	-1	25	6	26	1	21	2	22	3	23	4	24	5
	-11	25	20	26	15	21	16	22	17	23	18	24	19

B. Fuzzy DTC

The proposed fuzzy controller is Sugeno model, using triangular and trapezoidal membership for inputs, and constant (Vi, $i = 0, ... 26.$) for outputs.

(a)   (b)

(c)
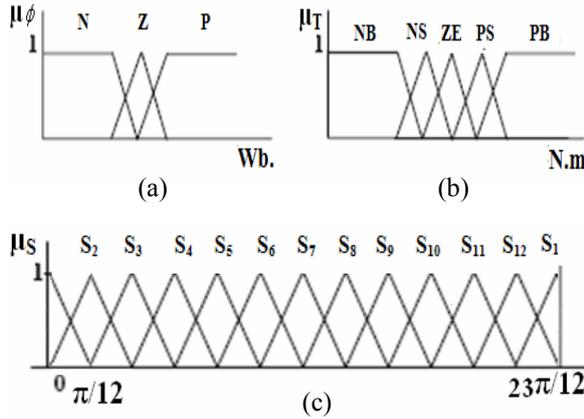
Fig.5. Membership functions of inputs of Fuzzy DTC. (a)Torque error(ΔT) ; (b) Flux error($\Delta \phi$) ; (c) Flux Sector(S)

In this approach, we replaced the two hysteresis controllers (basic DTC) and the switching table by a single fuzzy controller with torque error, flux error and Flux sector as inputs. The vector voltage of the inverter will be the control output.

The control strategy depends mostly on inference rules. The inference is based on the method of sum-product inference. To simplify the description of inferences, we use a table inference "Table II". For defuzzification, the center of gravity method was used
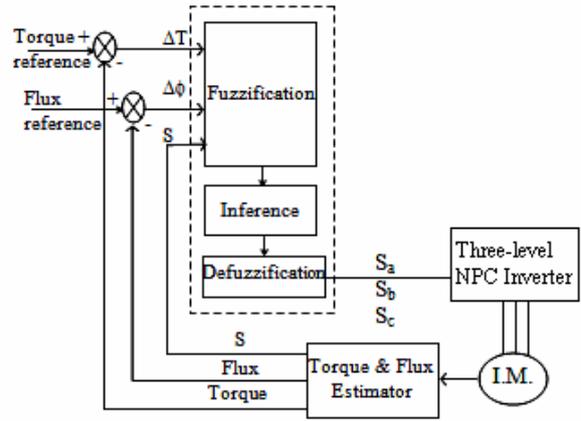
Fig.6. Induction Motor Fuzzy Direct Torque Control Block Diagram (Fuzzy DTC)

Φ	T	S											
		S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_3	S_9	S_{10}	S_{11}	S_{12}
P	PB	21	16	22	17	23	18	24	19	25	20	26	15
	PS	21	2	22	3	23	4	24	5	25	6	26	1
	ZE	Zero vector											
	NS	26	1	21	2	22	3	23	4	24	5	25	6
	NB	26	15	21	16	22	17	23	18	24	19	25	20
N	PB	17	23	18	24	19	25	20	26	15	21	16	22
	PS	3	23	4	24	5	25	6	26	1	21	2	22
	ZE	Zero vector											
	NS	5	25	6	26	1	21	2	22	3	23	4	24
	NB	19	25	20	26	15	21	16	22	17	23	18	24
Z	PB	22	17	23	18	24	19	25	20	26	15	21	16
	PS	22	3	23	4	24	5	25	6	26	1	21	2
	ZE	Zero vector											
	NS	25	6	26	1	21	2	22	3	23	4	24	5
	NB	25	20	26	15	21	16	22	17	23	18	24	19

C. Neural Network DTC

The neuron network with back propagation learning algorithm consists of an input layer, output layer and a hidden layer. The weighted connection between two successively layers have their values determined by the iterative learning stage.

Due to the parallel data processing, the learning capacity, the generalizing, and synthesizing properties; the neuron network can extract the adequate mathematical model from the presented input pattern and provide the good approximation of the desired target in the irrelevant case too [10].

In this approach, we replaced the switching table of basic DTC by a neural network controller with torque error ε_T, flux error ε_Φ and number of sector S as inputs. The vector voltage of the inverter will be the control output Vi, $i=0, ...26$.
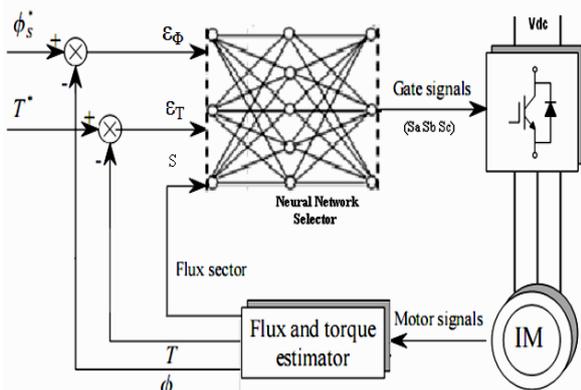
Fig. 7 Induction Motor Fuzzy Direct Torque Control Block Diagram (Neural network DTC)

The training of the neuron network to obtain the wished outputs was obtained with an error of 0.1%.

There are two hidden layers with 40 neurons in the first hidden layer and 50 neurons in the second hidden layer. The number of the off-line training epochs is 163 to reach the 0.001-imposed error "Fig 8".
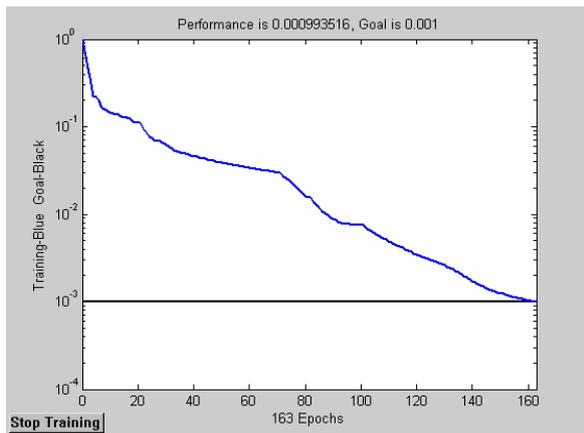
Fig. 8 Training Error of the Developed Neuron Network

IV. SIMULATION RESULTS

Specifications of the motor under control are summarized as follow:

TABLE III
CHARACTERISTICS OF THE INDUCTION MOTOR

F (Hz)	P (KW)	p	V (V)	Rs Ω	Rr Ω	Ls=Lr (H)	M (H)	J (kgm²)
50	1.5	2	280	0.5	1	0.105	0.1	0.02

Direct Torque Control modeling of induction motor was performed in the environment of Matlab-Simulink simulation. The DTC command structure is made with various blocks. The realization of neural network controller was through programming in Matlab (*.m files). The training was performed offline, and then the transition to the neural network control Simulink model will be called by Matlab function. Concerning the fuzzy controller, it is through the use of the toolbox of fuzzy logic which is called a file (*.Fis). In practice, there are two important factors that affect the performance of the DTC: the error bands, and sampling frequency. Concerning the error bands, the practice has shown that the choice to 4% of the nominal values gives the best operating range. This justifies the choice of this value in our simulation work.

A. General Performance of the System

"Fig. 9," shows the system start-up stabilization in order to observe its dynamic behavior under transient state, until it reaches its steady state. We observe that the control system reaches its steady state by showing good performance and great stability for the two approaches. The flux and torque stabilize around their reference values. $(Fs = 0.75 \ Wb.), (Ts = 10 N.m.)$.

(a)   (b)
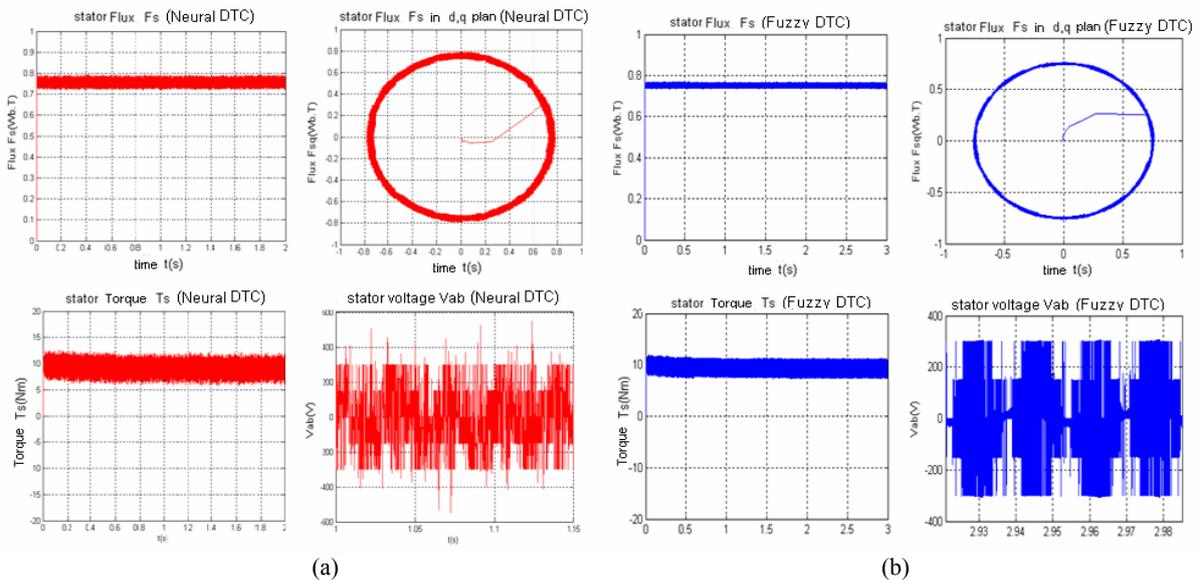
Fig.9. System response in start-up state $(Ts = 10 \ N.m, Fs = 0.75Wb.)$
(a) Neural DTC, (b) Fuzzy DTC

We note also, that the torque ripples are greater than the flux ripples. This is due to the stator phase currents, which directly affect the torque. The stability of the system can be observed over the stator phase voltage V$_{ab}$, which presents a periodic PWM form. The curves obtained by the controllers for the two approaches have the same look, except a slight difference, which is observed at the start-up state:

- In the neural network DTC, the flux reaches its reference and stabilizes in steady slightly faster but it gave large ripples than the Fuzzy DTC.
- Voltage dynamic given by Fuzzy DTC was better than those given by the neural network DTC.

B. Steady Performance of the System

To observe the robustness and system performance in steady state, we conducted the simulation in order to observe the influence of references (torque and flux) with a test of an inversion of torque, and a variation of flux simultaneously. This test is done to illustrate and to demonstrate the decoupling control between the torque and flux for the two approaches. "Fig10".

It can therefore be noted that the inversion of the couple does not affect the stability of flux and the variation of the flux does not also affecting the stability of the torque. We conclude that the problem of coupling characterizing the induction motor has been solved by our control system.

V. CONCLUSION

DTC with a Neutral Point Clamped (NPC) Inverter has been studied in the present work. Due to the enhanced possibilities for the inverter state selection in a three-level inverter an intelligent controller has been designed in order to replace the conventional method based on a switching table. This approach provides a more accurate selection of the inverter state by introducing fuzzy and neural network regulators.

We believe that we applied a structure of identification of nonlinear systems. The effectiveness of this structure was shown by simulation by giving satisfactory results

VI. REFERENCES

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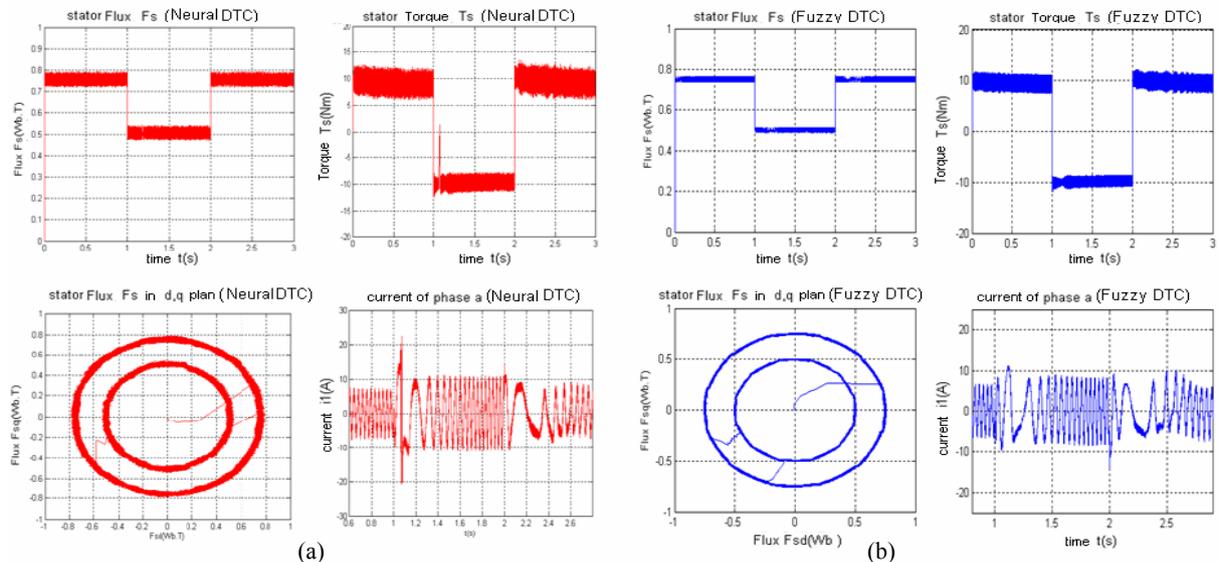
Fig.10. Inversion of torque $(+10 \rightarrow -10 \rightarrow +10 \ N.m.)$ and a variation of the flux. $(0.75 \rightarrow \ 0.5 \rightarrow \ 0.75 \ Wb.)$
(a) Neural DTC. (b) Fuzzy DTC