Algerian Journal of Research and Technology
AJRTDZ@gmail.com
http://www.univ-usto.dz/AJRT/

ISSN : 2543-3954 A.J.R.T Volume 2 (N° 1) (2018) 31-45

Fuzzy Speed Control of Induction Motor with Five-Level DTC-Based Neural Networks

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Abstract.
Direct Torque Control (DTC) is a control technique in AC drive systems to obtain high-performance torque control. In this paper, the Author presents the induction motor speed control with five-level DTC. This paper proposes to replace the selector switches statements of the voltage inverter by a selector based on Artificial Neural Network (ANN), which is able to manage in the same way the switches states, without resorting to complex programming. The speed loop regulation is carried out by a fuzzy controller giving the exceeding performance in comparison with a classic PI controller. The performance of the DTC-Artificial Neural Network (DTC-ANN) & DTC-ANN with the fuzzy PI controller is tested through Matlab/Simulink. The simulation results, which illustrate the performance of the proposed control scheme in comparison with the DTC-ANN scheme are given.

Keywords. DTC, Induction motor, Fuzzy PI controller, Artificial neural network, Five-level.

INTRODUCTION

The direct torque control (DTC) method has emerged as an alternative to field oriented control (FOC) method for high performance AC drives since it was firstly proposed in the mid 1980 (Kumar et al., 2012). DTC provides very quick response with simple control structure and hence, this technique is gaining popularity in industries (Idir et al., 2013).. The DTC utilizes hysteresis band controllers for both the stator flux-linkage and motor developed torque controls. The DTC uses flux and torque as primary control variables which are directly obtained from the motor (Sreenivasa et al., 2012).
On the other hand, multilevel inverters have been developed to overcome harmonics in output, and improve the shape of output to reach sinusoidal waveform (Mohana et al., 2010). The diode clamed multilevel inverters are based on the neutral point clamed inverter topology proposed by Nabae and al. And first cited in patent. For high power drive applications, three level inverter based drives and control schemes have been extensively studied. The trend toward a greater number of levels is necessitated by advantages of higher voltage ratings (Simha et al., 2000).

The multilevel direct torque control of electrical drives has become an attracting topic in research and academic community over the past decade (Benyoussef et al., 2015). In the aim to improve the performance of the electrical drives based on traditional DTC, Fuzzy logic direct torque control (FLDTC) and artificial neural network direct torque control (DTC-ANN) attracts more and more the attention of many scientists (Benyoussef et al., 2015).
In this paper, two strategies of five-level direct torque control are proposed and compared: a neural direct torque control (DTC-ANN) and a DTC-ANN control with the fuzzy PI controller. Five-level DTC based on AI techniques are applied to overcome some disadvantages of five-level DTC such as minimizing the torque, current and flux ripple. The paper is organized as follows. In section 2, a brief layout to the five-level inverter is presented. Then, we give more details on DTC in section 3. In sections 4 and 5 we present and discuss the DTC-ANN and DTC-ANN with the fuzzy PI controller approaches respectively. In section 6 we carry out a comparative study between all two DTC strategies: DTC-ANN, DTC-ANN with Fuzzy PI controller. In the final section, we conclude the paper.

FIVE-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 (Kadri et al., 2011). Typically, there are three types of multilevel inverters topologies. Those types are the neutral point clamped (NPC), flying capacitor (FC) and cascaded H-bridge multilevel inverters (CHMI) (Ramahlingam et al., 2016). Figure 1 shows a schematic diagram of a three-phase five-level diode-clamped VSI inverter. In this circuit, the DC-bus voltage is split into five levels by four series-connected bulk capacitors, C1, C2, C3, and C4. Ideally, each capacitor voltage is equal to Vcj=(Vdc/4), j=1,…,4 and each generated phase voltage has five levels with respect to the voltage of middle point ‘0’, -Vdc/2, -Vdc/4, 0, Vdc/2, and Vdc/4 (Benyoussef et al., 2014).

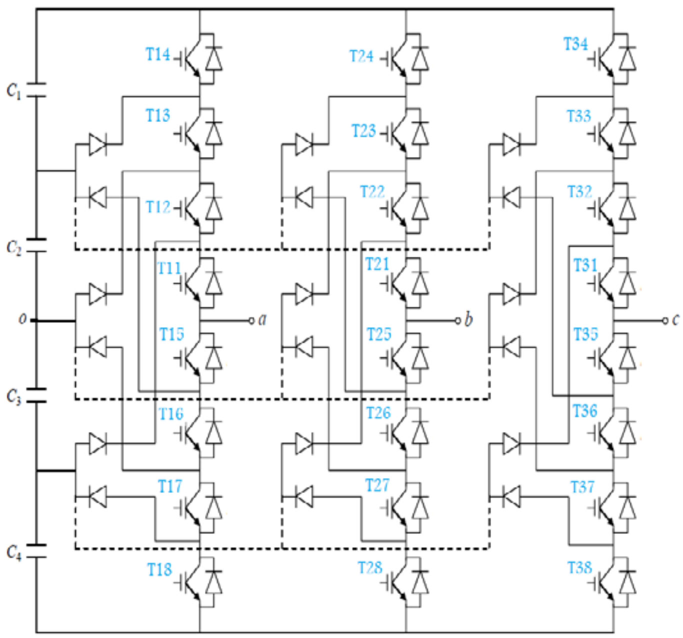


Fig. 1. Five-level diode clamped voltage source inverter.

The necessary conditions for the switching states for the five-level inverter are that the dc-link capacitors should not be shorted, and the output current should be continuous (Abdelkrim et al., 2016). The representation of the space voltage vectors of a five-level inverter for all switching states is given by figure 2.

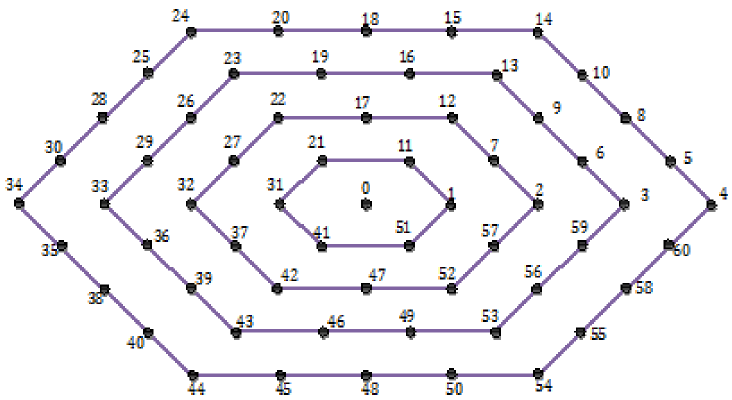


Fig. 2. Space vector diagram of five-level inverter.

FIVE-LEVEL DTC STRATEGY

The block diagram of the proposed sensorless control scheme is shown in figure 3. The DTC method was introduced in 1985 by Takahashi (Abbou et al., 2009). The instantaneous values of flux and torque are calculated from the measured variables of the IM and directly controlled by selecting an optimum switching state of the inverter so that the required optimum voltage vector is generated (Ahmed et al., 2012).

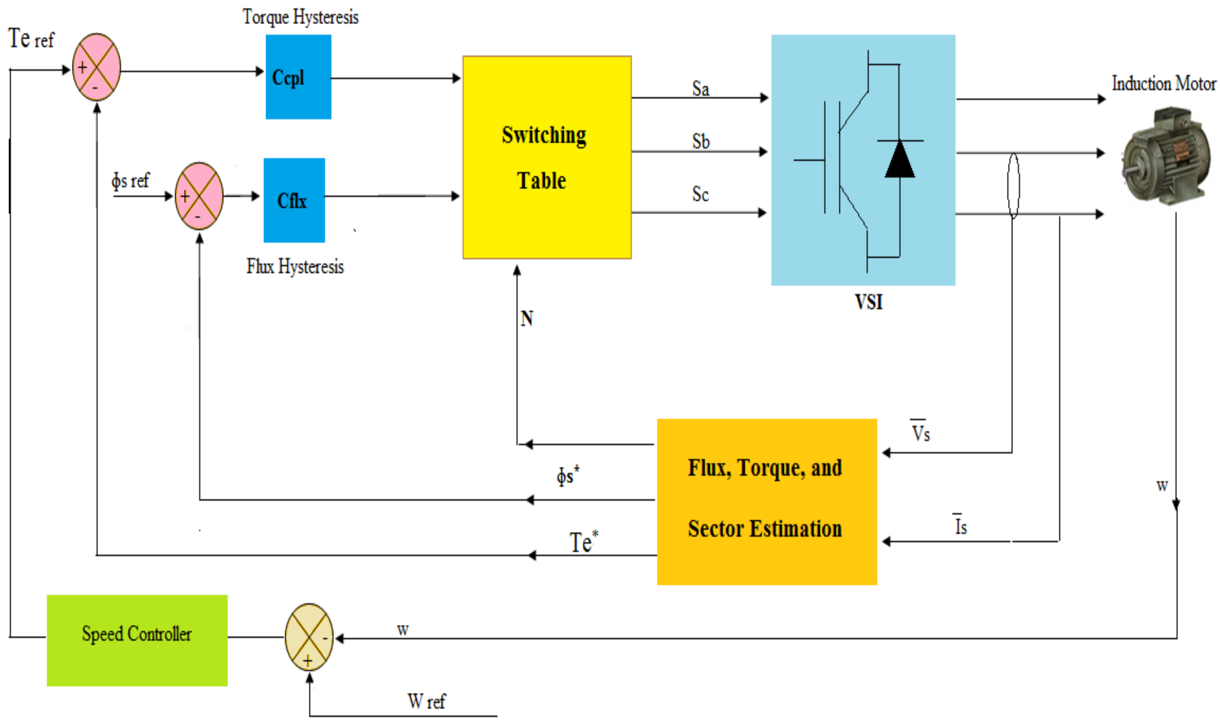


Fig. 3. Block diagram of direct torque control of Induction machine.

The speed error of the motor is given to speed controller produces reference torque (Te ref). The reference flux is determined from Induction machine parameters (Φs ref) (Sudheer et al., 2016). The stator flux on the stationary reference axes αβ is estimated as follows (Gdaim et al., 2010):

$$\begin{cases} \Phi_{s\alpha} = \int_0^t (v_{s\alpha} - R_s i_{s\alpha})dt \\ \Phi_{s\beta} = \int_0^t (v_{s\beta} - R_s i_{s\beta})dt \end{cases} \tag{1}$$

Where:

$$\Phi_s = \sqrt{\Phi_{s\alpha}^2 + \Phi_{s\beta}^2} \tag{2}$$

The angle θs is equal to (Mouna et al., 2016):

$$\theta_s = arctg(\frac{\Phi_{s\beta}}{\Phi_{s\alpha}}) \tag{3}$$

The electromagnetic torque is calculating by using:

$$T_e = \frac{3}{2} p\left[\Phi_{s\alpha} i_{s\beta} - \Phi_{s\beta} i_{s\alpha}\right] \tag{4}$$

The switching table proposed, as given by Table 1.

Table 1. Switching table for five-level DTC with 12 sectors.

	N	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**
Cflx	**Ccpl**												
	+6	14	14	24	24	34	34	44	44	54	54	4	4
	+5	15	20	25	30	35	40	45	50	55	60	5	10
	+4	18	18	28	28	38	38	48	48	58	58	8	8
	+3	13	13	23	23	33	33	43	43	53	53	3	3
	+2	9	19	16	26	19	29	36	39	46	49	59	6
	+1	12	12	22	22	32	32	42	42	52	52	2	2
1	**0**	0	0	0	0	0	0	0	0	0	0	0	0
	-1	52	52	2	2	12	12	22	22	32	32	42	42
	-2	56	59	6	9	16	19	26	29	36	39	46	49
	-3	53	53	3	3	13	13	23	23	33	33	43	43
	-4	58	58	8	8	18	18	28	28	38	38	48	48
	-5	55	60	5	10	15	20	25	30	35	40	45	50
	-6	54	54	4	4	14	14	24	24	34	34	44	44
	+6	17	17	27	27	37	37	47	47	57	57	7	7
	+5	17	17	27	27	37	37	47	47	57	57	7	7
	+4	17	17	27	27	37	37	47	47	57	57	7	7
	+3	11	11	21	21	31	31	41	41	51	51	1	1
	+2	11	11	21	21	31	31	41	41	51	51	1	1
	+1	11	11	21	21	31	31	41	41	51	51	1	1
0	**0**	0	0	0	0	0	0	0	0	0	0	0	0
	-1	0	0	0	0	0	0	0	0	0	0	0	0
	-2	41	41	51	51	1	1	11	11	21	21	31	31
	-3	47	47	57	57	7	7	17	17	27	27	37	37
	-4	42	42	52	52	2	2	12	12	22	22	32	32
	-5	46	49	56	59	6	9	16	19	26	29	36	39
	-6	43	43	53	53	3	3	13	13	23	23	33	33
	+6	24	24	34	34	44	44	54	54	4	4	14	14
	+5	25	30	35	40	45	50	55	60	5	10	15	20

	+4	28	28	38	38	48	48	58	58	8	8	18	18
	+3	23	23	33	33	43	43	53	53	3	3	13	13
	+2	19	26	29	36	39	46	49	56	59	6	16	9
	+1	22	22	32	32	42	42	52	52	2	2	12	12
-1	**0**	0	0	0	0	0	0	0	0	0	0	0	0
	-1	42	42	52	52	2	2	12	12	22	22	32	32
	-2	46	49	56	59	6	9	16	19	26	29	36	39
	-3	43	43	53	53	3	3	13	13	23	23	33	33
	-4	48	48	58	58	8	8	18	18	28	28	38	38
	-5	45	50	55	60	5	10	15	20	25	30	35	40
	-6	44	44	54	54	4	4	14	14	24	24	34	34

Figures 4 and 5 illustrate the flux and torque hysteresis comparators, respectively.

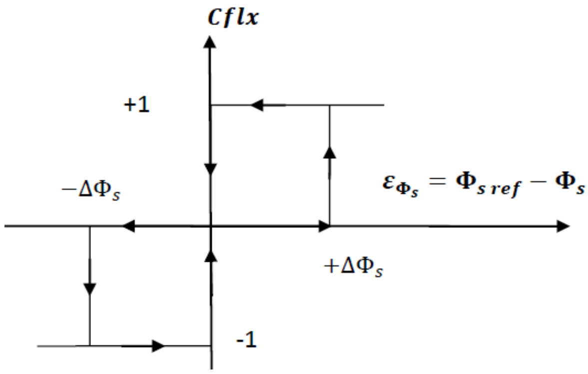


Fig. 4. Flux hysteresis comparator.

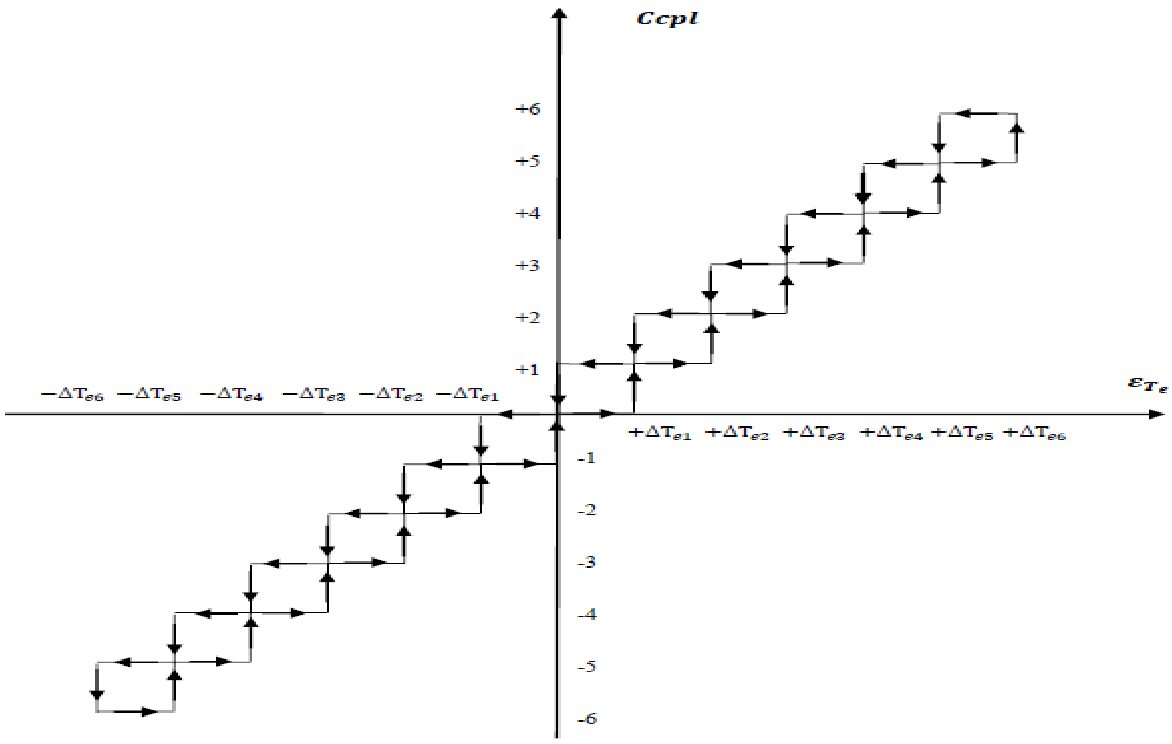


Fig. 5. Torque hysteresis comparator.

DTC BASED NEURAL NETWORK (DTC-ANN)

ANN's have been proven to be universal approximators of non-linear dynamic systems. They are able to emulate any complex non-linear dynamic system by using an appropriate multilayer neural network. After being used for many years in pattern recognition and signal and image processing applications, ANN's are now employed in a larger class of scientific disciplines. Many applications have been reported in power electronics, including fault detection and diagnosis in electrical machines, power converter control and the high performance control of electrical drives (Miloudi et al., 2007). The Artificial neural network replaces the switching table selector block (Fig. 6). He uses a dense interconnection of computing nodes to approximate nonlinear function (Abbou et al., 2006).

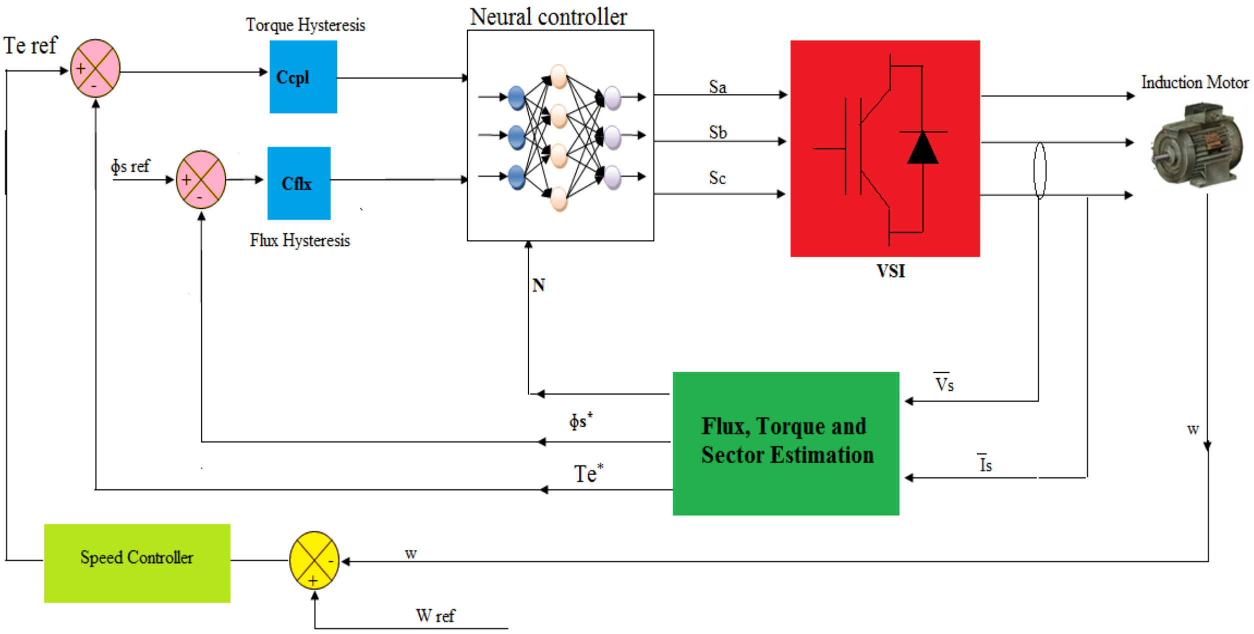


Fig. 6. DTC-ANN control of IM.

The ANN is trained by a learning algorithm which performs the adaptation of weights of the network iteratively until the error between target vectors and the output of the ANN is less than an error goal. The most popular learning algorithm for multilayer networks is the back propagation algorithm and its variants. The latter is Implemented by many ANN software packages such as the neural network toolbox from Matlab (Kumar et al., 2014). The structure of the neural network to perform the five-level DTC applied induction motor satisfactorily was a neural network with three linear input nodes, 30 neurones in the hidden layer, and three neurones in the output layer. The ANN switching table is shown in figure 7. The ANN is composed of two Layer, Layer 1 and Layer 2 (Fig. 8, Fig. 9).

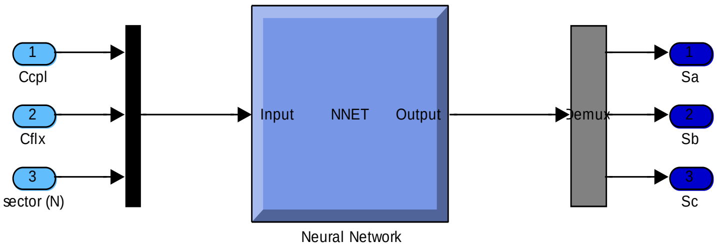


Fig. 7. ANN switching table

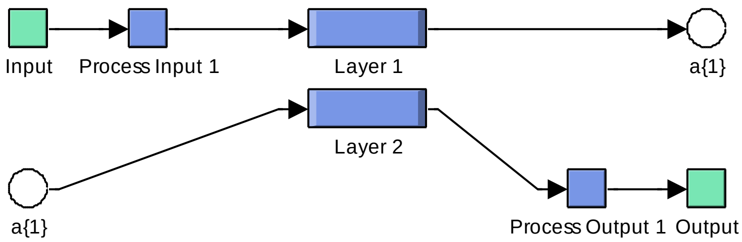


Fig. 8 Structure of ANN switching table

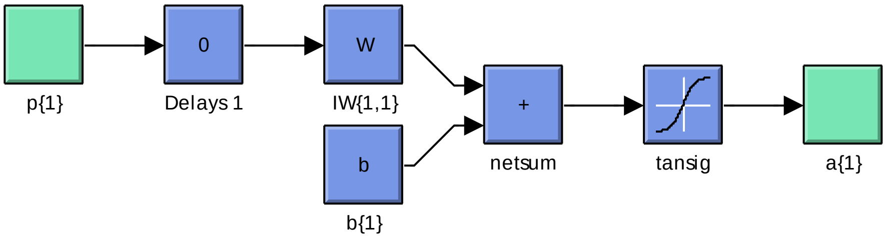


Fig. 9. Structure of Layer 1.

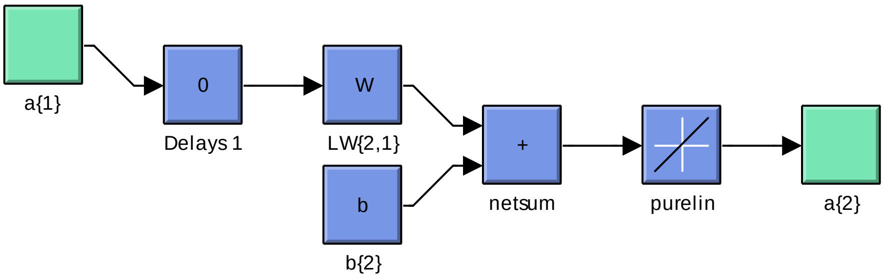


Fig. 10. Structure of Layer 2.

DTC-ANN WITH FUZZY PI CONTROLLER

In order to improve the DTC-ANN performances, a complimentary use of the fuzzy controller is proposed. The PI controller of DTC-ANN will be complimented with fuzzy PI controller (Fig.11).

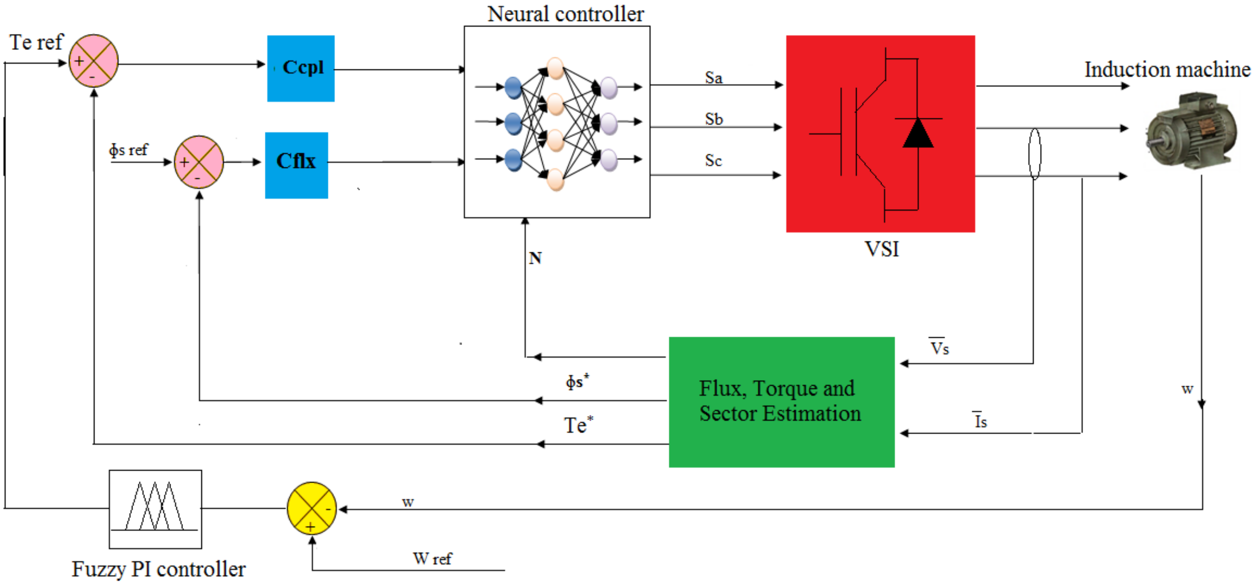


Fig. 11. DTC-ANN with fuzzy PI controller.

The fuzzy control is basically nonlinear and adaptive in nature, giving robust performance under parameter variation and load disturbance effect(Tahour et al., 2006). Fuzzy logic speed controller design is designed based on the human expert knowledge rule base. It does not require any mathematical model of the plant. Fuzzy control can be applied in the speed loop of Direct Torque control of induction motor (Sudheer et al., 2016).
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 (Youb et al., 2009). The block diagram of the Fuzzy PI controller (Fig. 12).

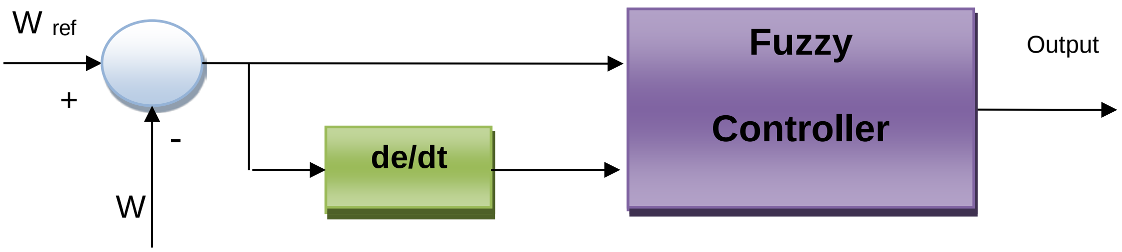


Fig. 12. Fuzzy logic control of speed.

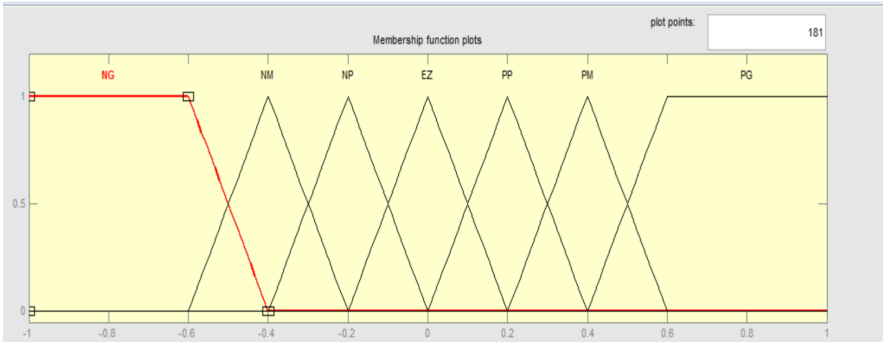
One possible initial rule base, that can be used in drive systems for a fuzzy logic controller, consist of 49 linguistic rules, as shown in Table 2, and gives the change of the output of fuzzy logic controller in terms of two inputs: the error (e = W ref - W) and change of error (de).

Table 2. Fuzzy Rules of Speed.

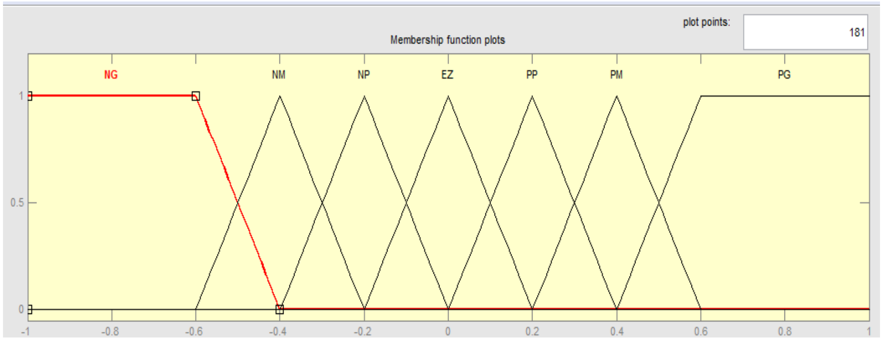
e / **Δe**	**NL**	**NM**	**NP**	**EZ**	**PS**	**PM**	**PL**
NL	NL	NL	NL	NL	NM	NP	EZ
NM	NL	NL	NL	NM	NP	EZ	PS
NP	NL	NL	NM	NP	EZ	PS	PM
EZ	NL	NM	NP	EZ	PS	PM	PL
PS	NM	NP	EZ	PS	PM	PL	PL
PM	NP	EZ	PS	PM	PL	PL	PL

PL	EZ	PS	PM	PL	PL	PL	PL

Figures 13 and 14 shows the membership functions of input and output variables respectively.



a) Error



b) Change in error

Fig. 13. Input variables membership functions.

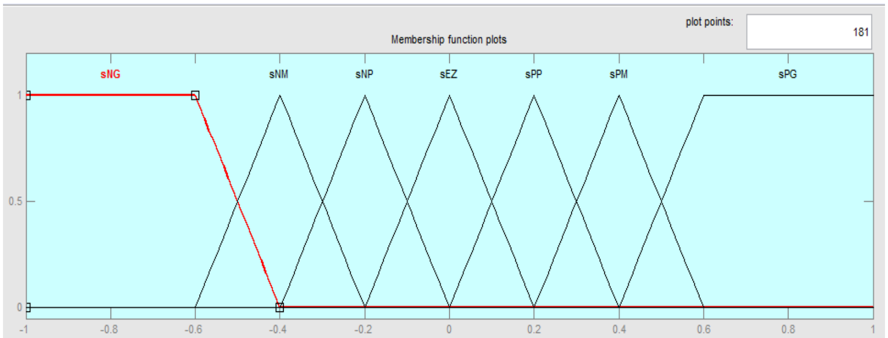
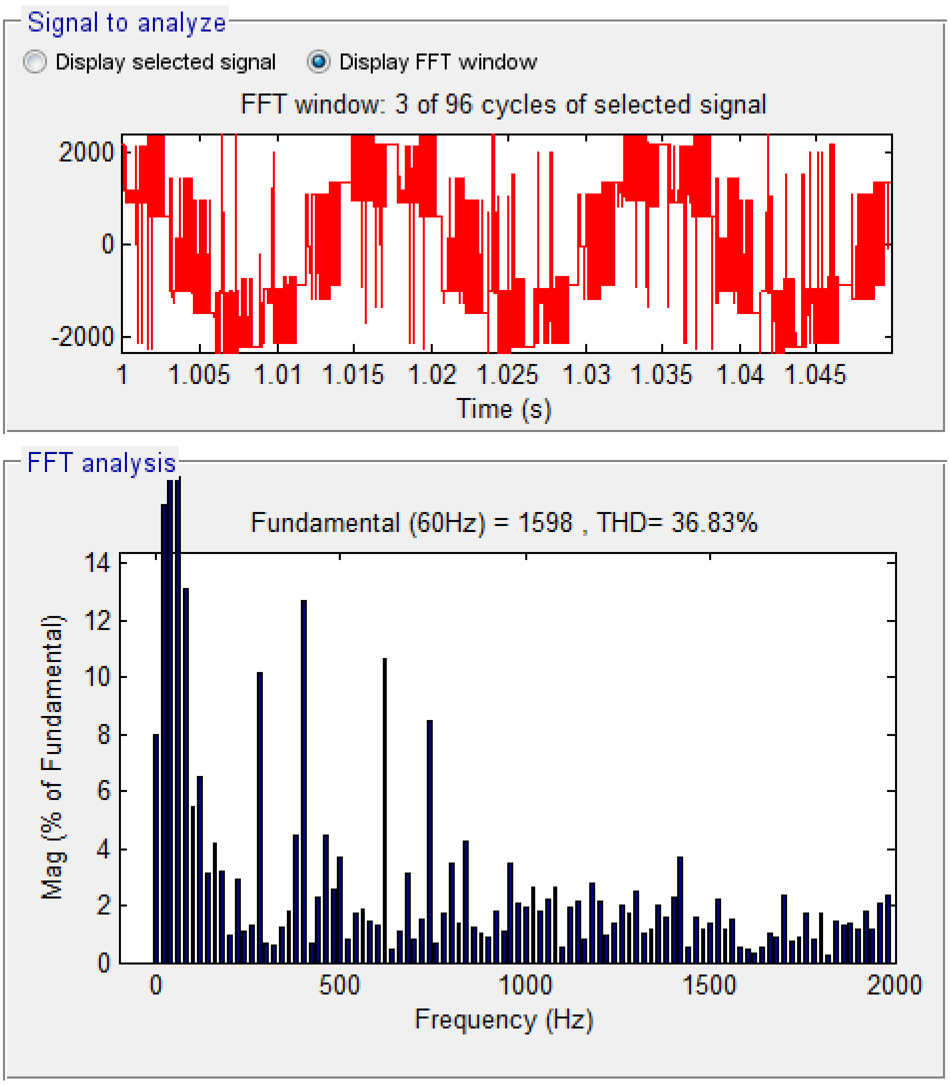


Fig. 14 .Output variable membership function.

SIMULATION RESULTS

To test the performances of the DTC-ANN control and DTC-ANN with fuzzy PI controller, the simulation of the systems was conducted using the MATLAB tool. The performance analysis is done with stator current, sector, stator flux and torque. Figures 15-16 shows the performances of the DTC-ANN control and DTC-ANN with the fuzzy PI controller. The torque and flux references used in the simulation results of the DTC-ANN control and DTC-ANN with the fuzzy PI controller are 6500 N.m and 3.6 wb respectively. The machine is running at 1000 tr/min. All four figures are the responses to step change torque command from zero to 6500 N.M, which is applied at 0.8 s.



Signal to analyze
Display selected signal
Display FFT window
FFT window: 3 of 96 cycles of selected signal
2000
0
-2000
1
1.005
1.01
1.015
1.02
1.025
1.03
1.035
1.04
1.045
Time (s)
FFT analysis
Fundamental (60Hz) = 1598 , THD= 36.83%
Mag (% of Fundamental)
14
12
10
8
6
4
2
0
0
500
1000
1500
2000
Frequency (Hz)

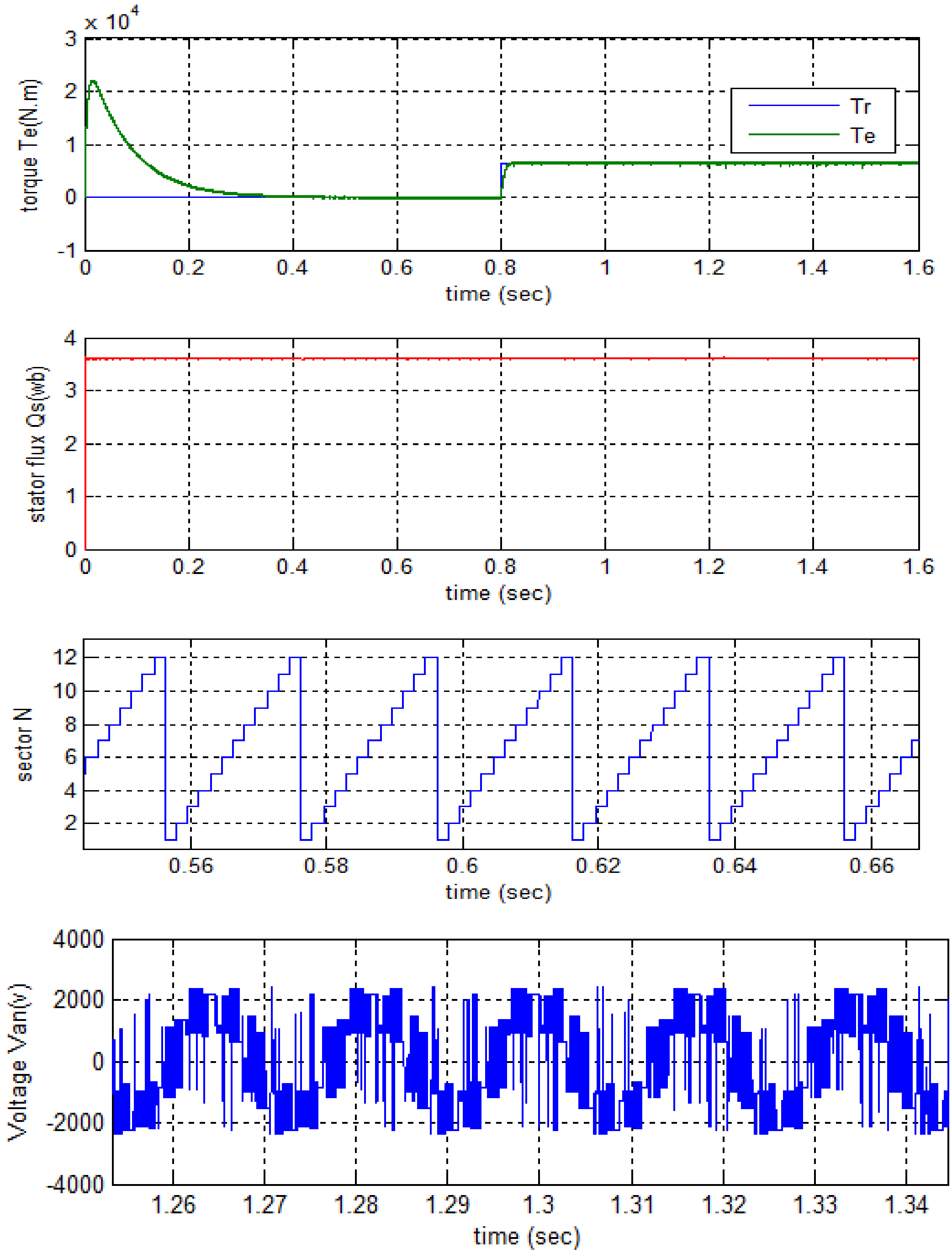
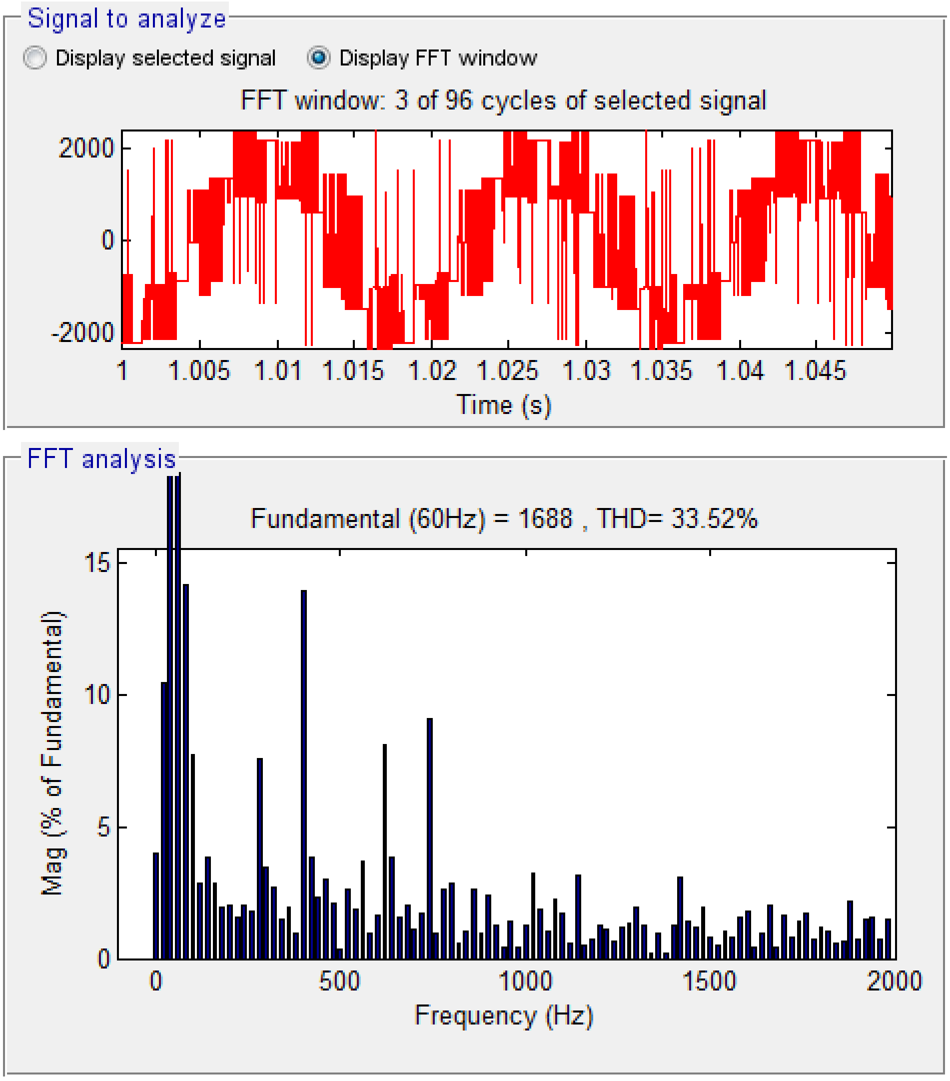
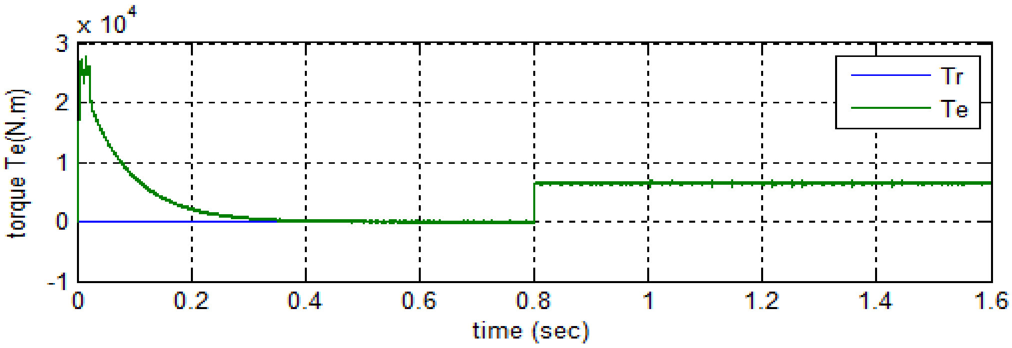
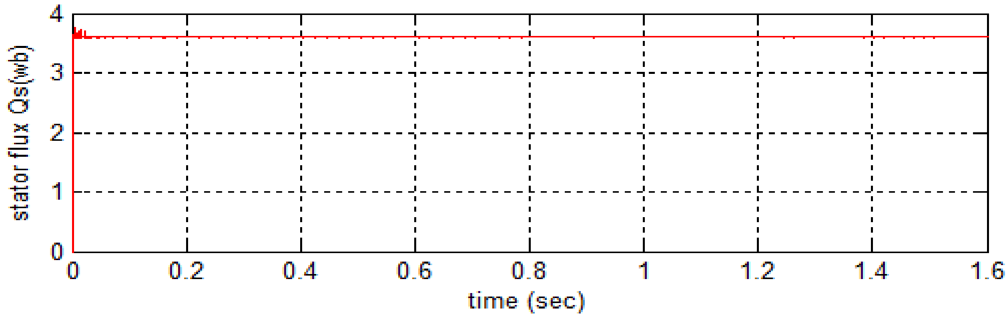


Fig. 15. Performances of DTC-ANN for IM.


Signal to analyze
Display selected signal
Display FFT window
FFT window: 3 of 96 cycles of selected signal
2000
0
-2000
1 1.005 1.01 1.015 1.02 1.025 1.03 1.035 1.04 1.045
Time (s)
FFT analysis
Fundamental (60Hz) = 1688 , THD= 33.52%
Mag (% of Fundamental)
15
10
5
0
0 500 1000 1500 2000
Frequency (Hz)


x 10^4
torque Te(N.m)
3
2
1
0
-1
Tr
Te
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6
time (sec)


stator flux Qs(wb)
4
3
2
1
0
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6
time (sec)

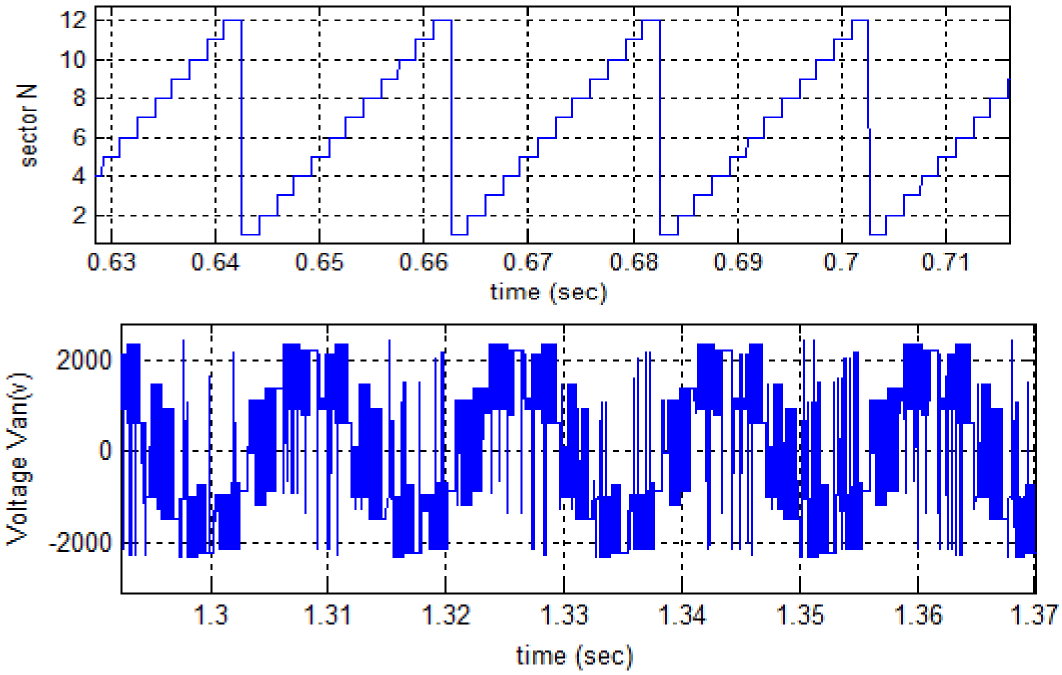
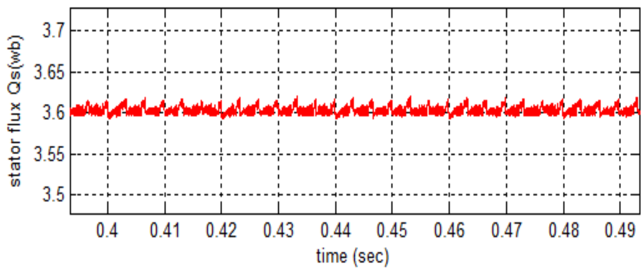
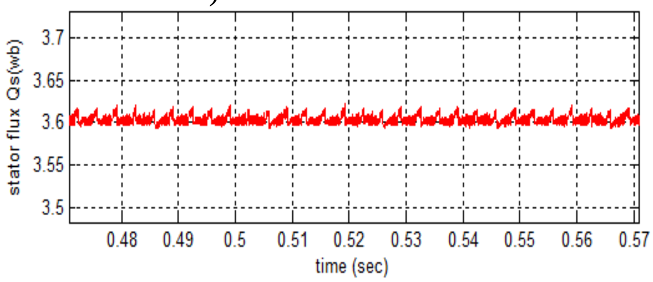


Fig. 16. Performances of DTC-ANN with fuzzy PI controller.

Figures 17-18 shows that the DTC-ANN with the fuzzy PI controller significantly reduces the ripple of the electromagnetic torque and stator flux compared to that of the DTC-ANN.

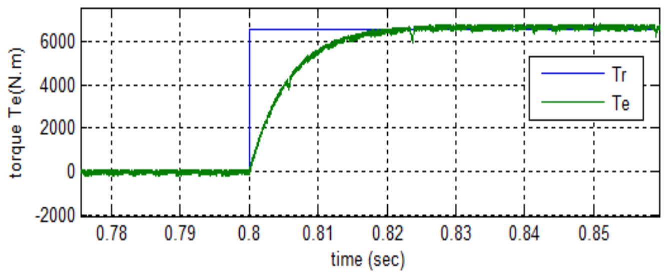


a)DTC-ANN

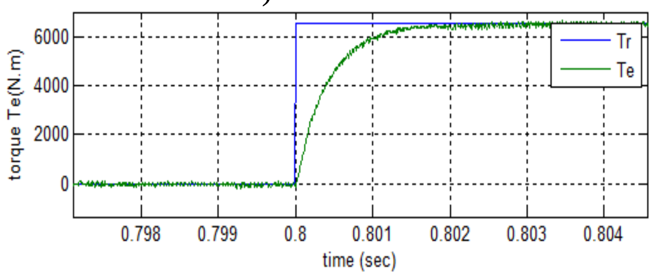


b) DTC-ANN with fuzzy PI controller

Fig. 17. Zoom in the flux.



a)DTC-ANN



b) DTC-ANN with fuzzy PI controller

Fig. 18. Zoom in the Torque.

In Table 3, we summarize the simulation results obtained by five-level DTC-ANN and the DTC-ANN with the fuzzy PI controller.

It can be concluded from Table 3 that DTC-ANN with the fuzzy PI controller is more efficient than the DTC-ANN command of the induction motor powered by the five-level inverter.

Table 3. Comparison between the Five-Level DTC-ANN and the DTC-ANN with Fuzzy PI Controller.

	Five-level DTC-ANN	Five-level DTC-ANN with fuzzy PI controller
Van THD (%)	36.83	**33.52**

In the other hand, the dynamics of the components of the stator flux are not affected by the application of these load guidelines.

CONCLUSION

In this paper, two different DTC with the five-level inverter will be compared with each other. These two schemes are DTC-ANN, DTC-ANN with the fuzzy PI controller. The simulation results obtained for the five-level DTC-ANN with the fuzzy PI controller illustrate a considerable reduction in torque ripple, voltage ripple and stator flux ripple compared to the existing DTC-ANN with five-level inverter.

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Youb L., Craciunescu A., 2009. Proceedings of the World Congress on Engineering and Computer Science. 2.