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Seven-Level Direct Torque Control of Induction Motor Based on Artificial Neural Networks with Regulation Speed Using Fuzzy PI Controller

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Abstract: In this paper, the author proposes a sensorless direct torque control (DTC) of an induction motor (IM) fed by seven-level NPC inverter using artificial neural networks (ANN) and fuzzy logic controller. Fuzzy PI controller is used for controlling the rotor speed and ANN applied in switching select stator voltage. The control method proposed in this paper can reduce the torque, stator flux and total harmonic distortion (THD) value of stator current, and especially improve system good dynamic performance and robustness in high and low speeds.

Keywords: DTC, IM, Seven-Level NPC Inverter, ANN, Fuzzy PI, THD.

1 Introduction

TRADITIONALLY, variable speed electric machines were based on DC motors, since the magnetic flux and torque are easily controlled by the stator and rotor current, respectively. For the last two decades, DC motors was replaced by AC motors [1]. The induction machine (IM) known by its robustness, cost, reliability and effectiveness is the subject of several researches [2]. High performance electric drives require decoupled torque and stator flux command. This command is commonly provided through Field Oriented Control (FOC), which is based on decoupling of the torque-producing current component and the stator flux-producing component. FOC drive scheme requires current regulators and coordinate transformations. Current-regulated pulse-width-modulation (PWM) inverter and inner current loops degrade the dynamic performance in the operating regimes wherein the voltage margin is insufficient for the current command, particularly in the field weakening region [3].

The problem of decoupling the stator current in a dynamic fashion is avoided by direct torque control. DTC was introduced in 1985 by Takahashi and Depenbrock especially for the asynchronous and synchronous machines [4]. In DTC the torque and stator flux are directly controlled using the selection of the optimum voltage vector. The switching logic command facilitates the generation of the stator voltage space vector, with a suitable choice of the switching pattern of the inverter, on the basis of the knowledge of the sector and the amplitude of the stator flux and the torque. The DTC scheme is characterized by its simple implementation and its fast dynamic response [5].

Traditional DTC suffer from disadvantages like high torque and flux ripples under steady state due to presence hysteresis bands, poor performance at starting and low speeds and stator current distortions. These drawbacks of DTC control has been studied in the literature [6, 7]. In past decades researches came out with different type of solutions to improve the performance of the conventional DTC [8]. In order to reduce torque ripples, THD value of stator current artificial intelligence (AI) techniques like neural networks, Fuzzy logic are used to improve the performance of DTC control scheme.

In this paper, two different DTC schemes will be compared with each other. These two schemes are traditional DTC command with seven-level inverter and seven-level DTC-ANN with fuzzy speed regulator. The proposed command scheme is verified by both the simulation results. Simulation results show the clearly

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depicts reduction of stator flux, torque ripples, and THD value of stator current in proposed DTC scheme.

2 Seven-Level Inverter

Multilevel inverter structures have been developed to overcome shortcomings in solid-state switching device ratings so they can be applied to higher voltage systems [9]. In 1980, early interest in multilevel power conversion technology was triggered by the work of Nabae, who introduced the neutral-point-clamped (NPC) inverter topology [10]. The main concept of this inverter is to use diodes to limit the power devices voltage stress [11]. The topology that has been used in this paper is a three-phase full bridge seven levels diode clamped inverter and this topology is shown in Fig. 1 [12]. The voltage across the phase winding of the IM can attain one of the seven levels 6, 5, 4, 3, 2, 1 or 0 depending upon the switching states of the inverters.

The necessary conditions for the switching states for the seven-level inverter are that the DC-link capacitors should not be shorted, and the output current should be continuous [13].

The representation of the space voltage vectors of a seven-level NPC inverter for all switching states is given by Fig. 2 [14].

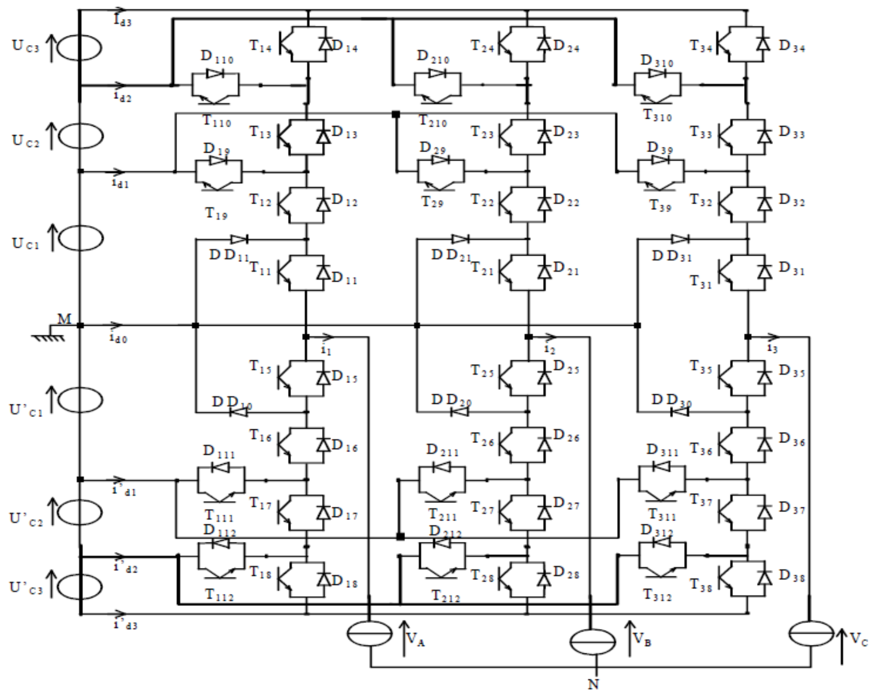

Fig. 1 Seven-level diode clamped voltage source inverter.

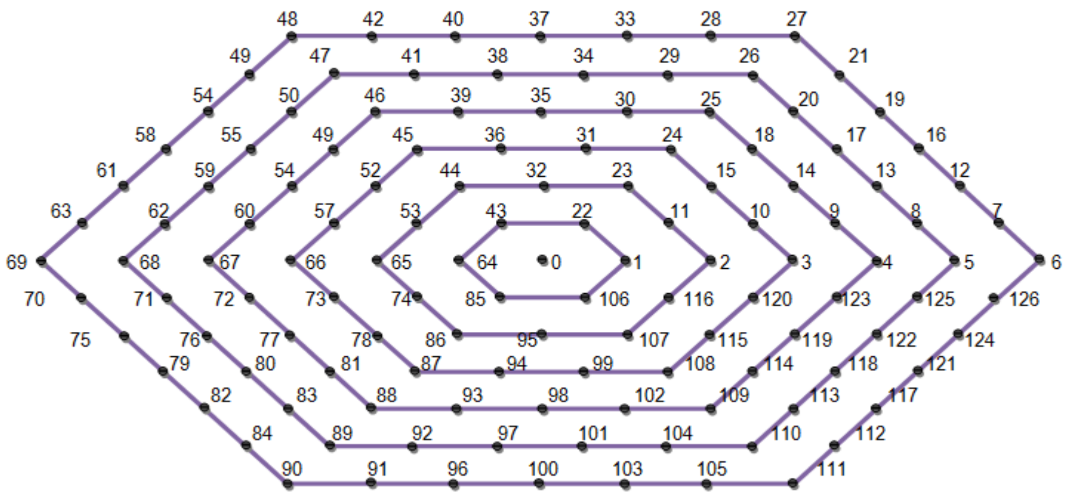

Fig. 2 Space vector diagram of seven-level NPC inverter.

3 Conventional DTC

The basic principle in traditional DTC for induction motors is to directly select stator voltage vectors by means of a hysteresis stator flux and electromagnetic torque command. As it is shown in Fig. 3 [15].

The DTC command is based on applying a switching series, which shall directly eliminate errors, which shall occur in electromagnetic torque, through the reference given as value and the calculated stator flux, to the power switching elements in the inverter. Other vector command methods are mostly based on rotor flux while DTC technique is based on stator flux [16].
The stator flux is estimated by equations [17,18]:

$$\Phi_s = \int_0^t (V_s - R_s . i_s) dt \tag{1}$$

with

$$\begin{cases} \Phi_{s\alpha} = \int_0^t (v_{s\alpha} - R_s i_{s\alpha}) dt \\ \Phi_{s\beta} = \int_0^t (v_{s\beta} - R_s i_{s\beta}) dt \end{cases} \tag{2}$$

The stator flux amplitude is given by

$$\Phi_s = \sqrt{\Phi_{s\alpha}^2 + \Phi_{s\beta}^2} \tag{3}$$

The stator flux angle is calculated by

$$\theta_s = \arctan(\frac{\Phi_{s\beta}}{\Phi_{s\alpha}}) \tag{4}$$

Electromagnetic torque equation is given by

$$T_e = \frac{3}{2} p \left[\Phi_{s\alpha} i_{s\beta} - \Phi_{s\beta} i_{s\alpha} \right] \tag{5}$$

The selection of the appropriate voltage vector is based on the switching table given in Table 1 (See Appendix). The input quantities are the stator flux position sector (N) and the digitized output variables Ccpl and Cflx. Thus, the selection table generates pulses Sa, Sb, Sc to control the power switches in the inverter.

In the seven-level DTC control, it employs a pair of hysteresis comparators, one utilizes a three-level hysteresis comparator for controlling the stator flux (Fig. 4) and the other one uses a seven-level hysteresis comparator for controlling the electromagnetic torque (Fig. 5).

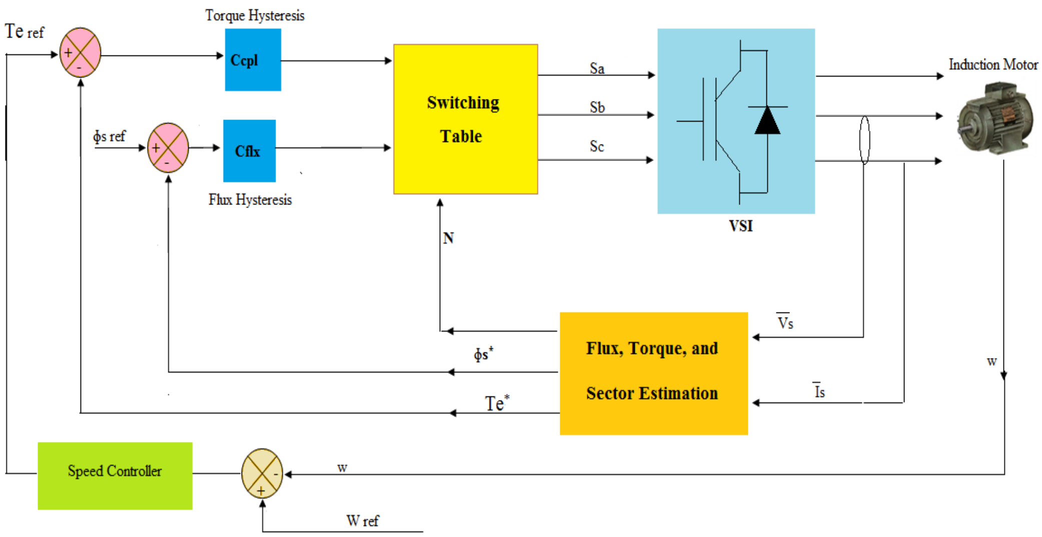

Fig. 3 Block diagram of classical DTC for IM.

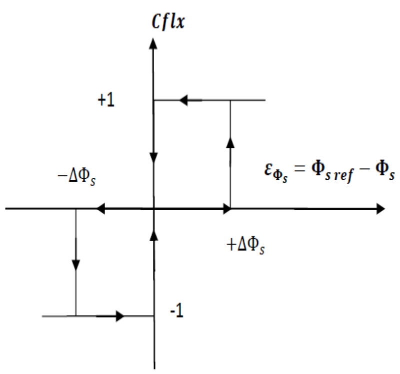

Fig. 4 Stator flux hysteresis comparator.

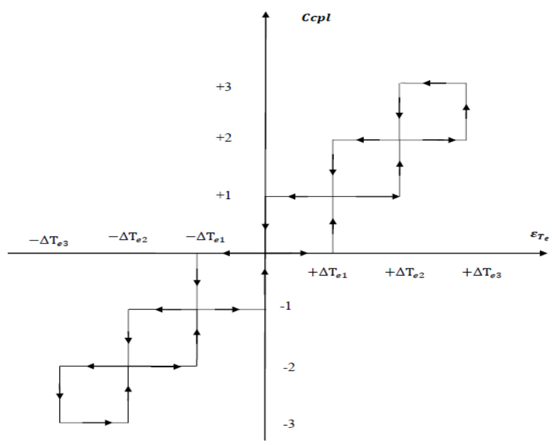

Fig. 5 Torque hysteresis comparator.

4 Seven-Level DTC-ANN with Fuzzy Controller

In order to improve the seven-level DTC performances a complimentary use of neural networks and fuzzy logic regulator is proposed. ANN is part of the family of statistical learning methods inspired by biological nervous system and are used to estimate and approximate functions that depends only on a large number of inputs [19].

A group of artificial neurons, which work in parallel, their inputs and outputs, have the same destination from a layer. Each neural networks must contain at least one layer of neurons but can join as many as someone projects. The layer gathering the neurons which give the output of the neural networks is called output layer. Layers which contain the neurons interposed between the global inputs of the neural network and the inputs of the neurons from the output layer are called hidden layers. Usually, there are used feed-forward NN which contains a hidden layer and an output layer [20]. In the other hand, fuzzy logic is recently getting increasing emphasis in drive control applications. Recent years, fuzzy logic control has found many applications in the past two decades. This is so largely increasing because fuzzy logic command has the capability to command nonlinear uncertain systems even in the case where no mathematical model is available for the command system [21].

The principle of neural networks direct torque command with fuzzy speed regulator is similar to traditional DTC. The difference is using a neural networks controller to replace the switching table and using fuzzy logic to replace the classical PI regulator of speed. As shown in Fig. 6.

4.1 Fuzzy Logic Based Speed Controller

The block diagram for fuzzy based speed regulator (classical PI) is shown in Fig. 7 [22]. The fuzzy regulator design is based on intuition and simulation [23]. The fuzzy logic rules are written by fascinating the performance of the PI regulator. The fuzzy logic rules for the proposed system are given in Table 2.

The Table 3 (See Appendix) shows the parameters of fuzzy regulator.

The block diagram of the fuzzy logic controller of the speed regulation is given by Fig. 8.

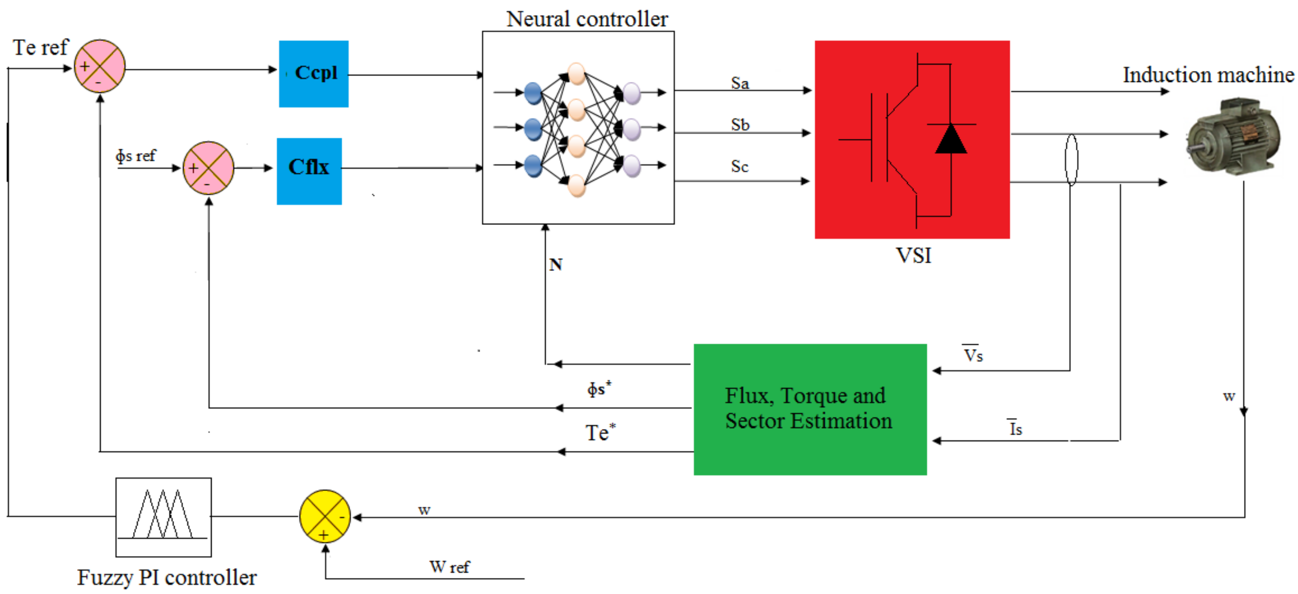

Fig. 6 DTC-ANN controls with fuzzy speed controller.

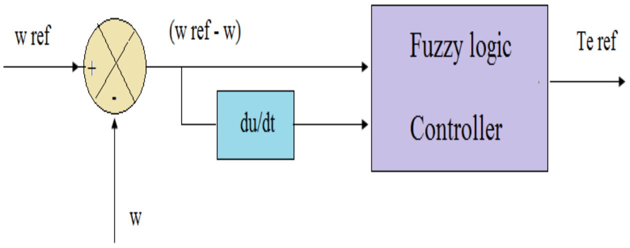

Fig. 7 Fuzzy logic command of speed regulation.

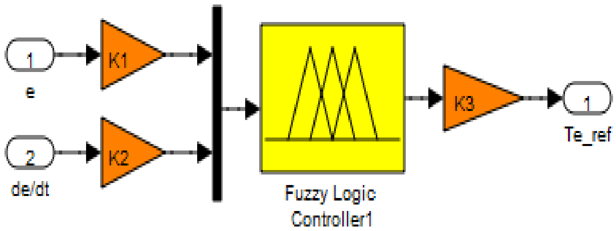

Fig. 8 Bloc diagram of the fuzzy controller.

Table 2 Fuzzy logic rules.

e / Δe	NB	NM	NS	EZ	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	EZ
NM	NB	NB	NB	NM	NS	EZ	PS
NS	NB	NB	NM	NS	EZ	PS	PM
EZ	NB	NM	NS	EZ	PS	PM	PB
PS	NM	NS	EZ	PS	PM	PB	PB
PM	NS	EZ	PS	PM	PB	PB	PB
PB	EZ	PS	PM	PB	PB	PB	PB

Here “e” is speed error and (Δe) is change in error. The membership function definition for the input variables “error in speed” is shown in Fig. 9, “change in error” is shown in Fig. 10.

We use the next designations for membership functions:

NB:	Negative Big	NM:	Negative Middle
NS :	Negative Small	PS :	Positive Small
PB :	Positive Big	EZ :	Equal Zero
PM:	Positive Middle		

4.2 Neural Based Switching Table

The ANN has many models, but the usual model is the multilayer feed forward network using the error back propagation algorithm. Such a neural network contains three layers: input layers, hidden layers and output layers. Each layer is composed of several neurons. The number of the neurons in the input and output layers depends on the number of the selected input and output variables. The number of hidden layers and the number of neurons in each depend on the desired degree of accuracy [24].

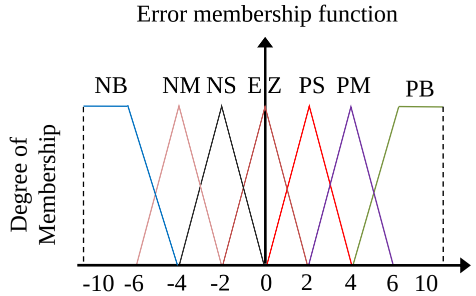

Fig. 9 Membership functions for error in speed.

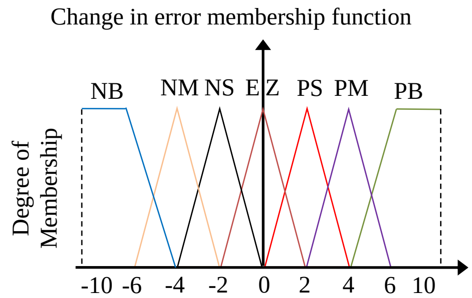

Fig. 10 Membership functions for change in error.

The convergence of the network in summer obtained by using the value of the parameters grouped in the Table 4.

In MATLAB command we generated the Simulink block ANN regulator of switching table (Table 1) by (gensim) given this model scheme show in Fig. 11.

The structure of the neural network to perform the seven-level DTC with 36 sectors applied IM satisfactorily was a neural networks with 3 linear input nodes, 30 neurons in the hidden layer, and 3 neurons in the output layer. As shown in Fig. 12. The ANN is composed of two layer, Layer 1 and Layer 2 (Fig. 13 and Fig. 14).

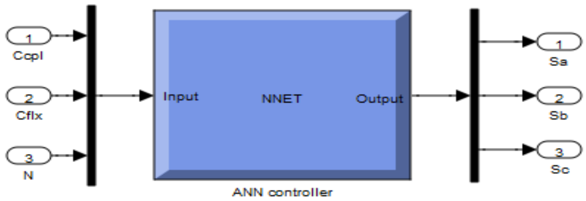

Fig. 11 Simulink block for ANN switching table.

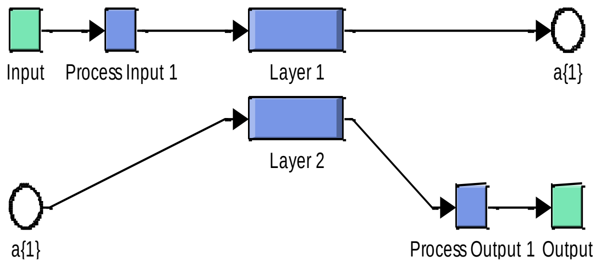

Fig. 12 Structure of ANN switching table.

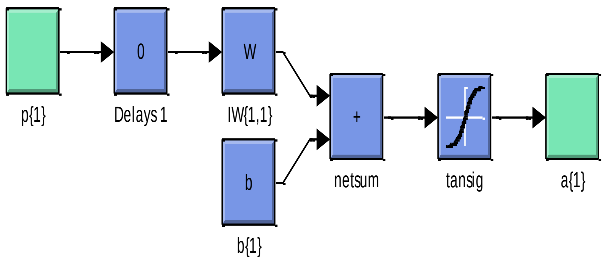

Fig. 13 Structure of layer 1.

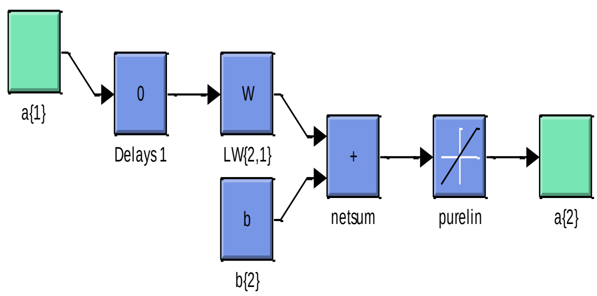

Fig. 14 Structure of layer 2.

5 Simulation Results

The simulation results of seven-level DTC-ANN with fuzzy speed controller of sensorless IM are compared with conventional seven-level DTC command. For this end, the commands system was tested under deferent operating conditions such as sudden change of load torque. The performance analysis is done with THD value, sector, speed, stator flux and torque. Fig. 15 show the performances of the seven-level DTC control and Fig. 16 show the performances of the seven-level DTC-ANN with the fuzzy speed controller. The torque and flux references used in the simulation results of the seven-level DTC control and DTC-ANN with the fuzzy speed regulator are 6500 N.m and 3.6 Wb respectively. The machine is running at 1000 rpm.

From the simulation results presented in Figs. 15-16 it is apparent that the THD value of stator current for the seven-level DTC with intelligent techniques (Neural network and fuzzy logic) is considerably reduced. Table 5 shows the comparative analysis of THD value for stator current.

Torque response comparing curves are shown in Fig. 17. See figure the torque ripple is significantly reduced when the intelligent techniques is in use.

Fig. 18 shows the stator flux responses of both the conventional and neural seven-level DTC with fuzzy speed controller. It is found that the proposed DTC scheme exhibits smooth response and lesser ripple in flux as compared to the conventional seven-level DTC scheme.

Table 5 Comparative analysis of THD value.

Conventional DTC with seven-level inverter	Seven-level DTC-ANN with fuzzy controller
26.92%	12.29%

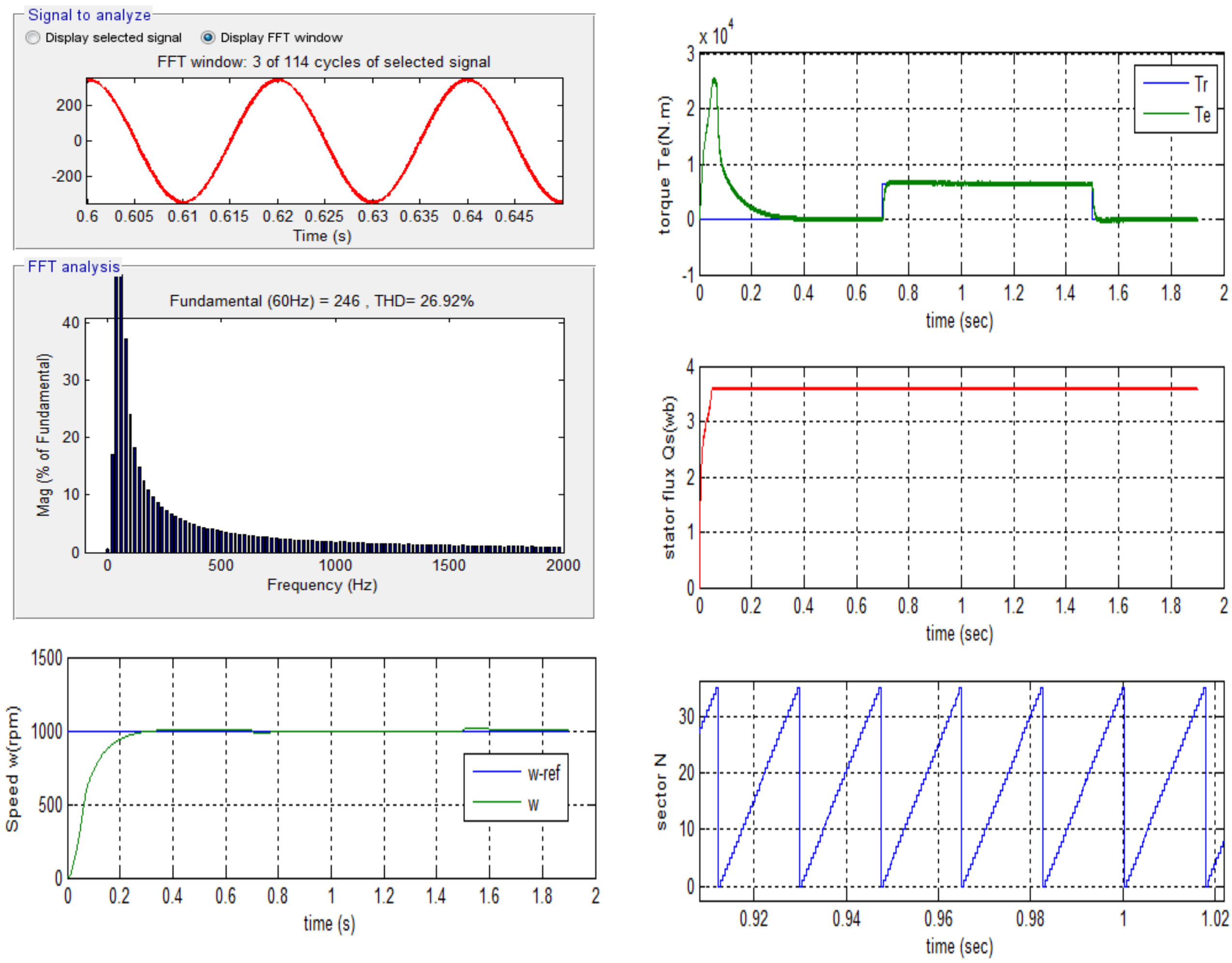

Fig. 15 Performances of seven-level DTC without fuzzy speed controller.

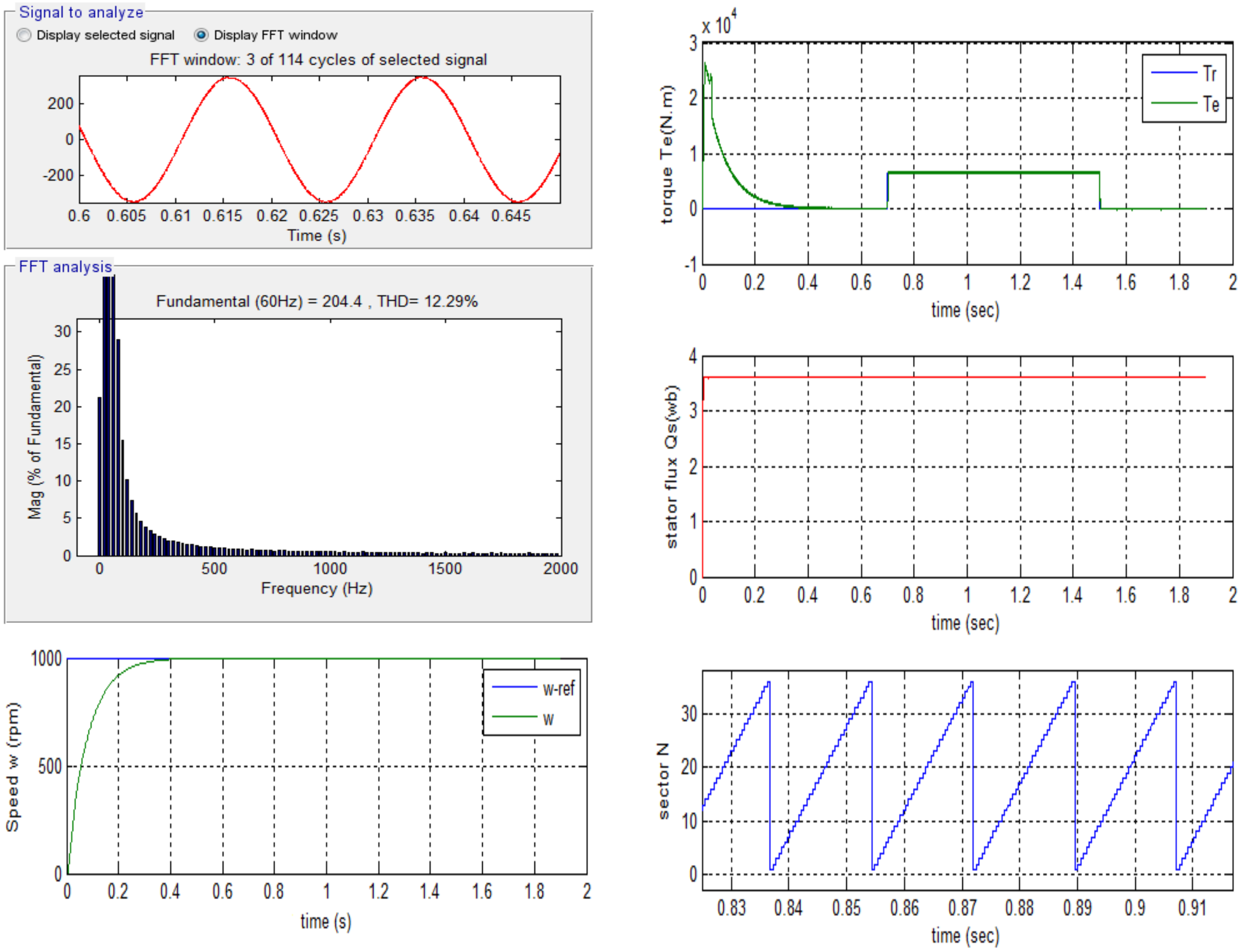

Fig. 16 Performances of seven-level DTC-ANN with fuzzy speed controller.

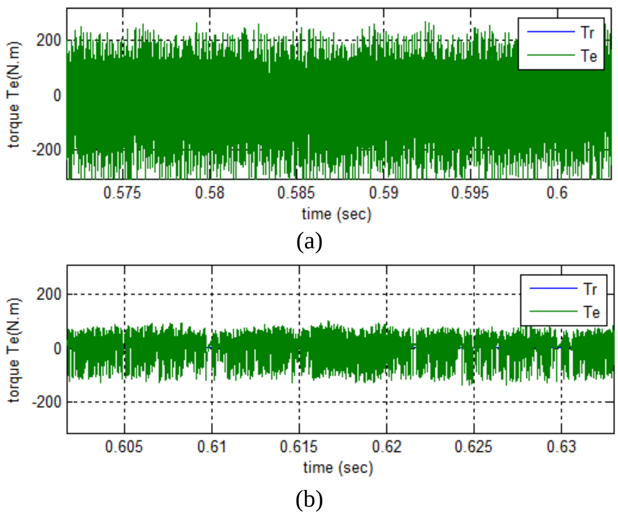

Fig. 17 Zomm in the torque, a) Seven-level DTC and b) Seven-level DTC-ANN with fuzzy speed controller.

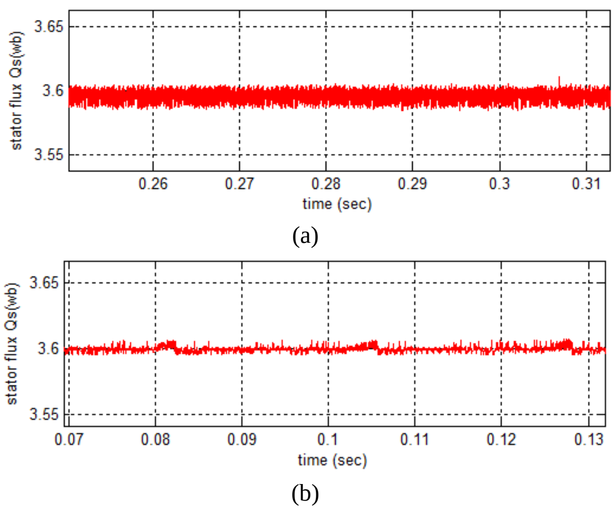

Fig. 18 Zomm in the stator flux, a) Seven-level DTC and b) Seven-level DTC-ANN with fuzzy speed controller.

6 Conclusions

In this paper, the 36 sectors DTC principle is presented and it is shown that with intelligent techniques (neural network and fuzzy logic) for a seven-level NPC inverter. The simulation results obtained for the seven-level DTC with intelligent techniques illustrate a considerable reduction in torque ripple, stator flux ripple and THD value of stator current compared to the traditional 36 sectors DTC utilizing seven-level NPC inverter.

Appendix

a) DTC Switching Table

Table 1 Seven-level DTC switching table with 36 sectors.

Cflx	Ccpl \ N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	3	27	28	33	37	40	42	48	49	54	58	61	63	69	70	75	79	82
	2	21	27	28	33	37	40	42	48	49	54	58	61	63	69	70	75	79
	1	19	21	27	28	33	37	40	42	48	49	54	58	61	63	69	70	75
	0	16	19	21	27	28	33	37	40	42	48	49	54	58	61	63	69	70
	-1	12	16	19	21	27	28	33	37	40	42	48	49	54	58	61	63	69
	-2	7	12	16	19	21	27	28	33	37	40	42	48	49	54	58	61	63
	-3	6	7	12	16	19	21	27	28	33	37	40	42	48	49	54	58	61
0	3	37	40	42	48	49	54	58	61	63	69	70	75	79	82	84	90	91
	2	37	40	42	48	49	54	58	61	63	69	70	75	79	82	84	90	91
	1	33	37	40	42	48	49	54	58	61	63	69	70	75	79	82	84	90
	0	33	37	40	42	48	49	54	58	61	63	69	70	75	79	82	84	90
	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	-2	100	103	105	111	112	117	121	124	126	6	7	12	16	19	21	27	28
	-3	100	103	105	111	112	117	121	124	126	6	7	12	16	19	21	27	28
-1	3	48	49	54	58	61	63	69	70	75	79	82	84	90	91	96	100	103
	2	47	50	55	59	62	68	68	71	76	80	83	89	89	92	97	101	104
	1	46	46	51	56	56	60	67	67	72	77	77	81	88	88	93	98	98
	0	5	8	13	17	20	26	26	29	34	38	41	47	47	50	55	59	62
	-1	26	26	29	34	38	41	47	47	50	55	59	62	68	68	71	76	80
	-2	89	92	97	101	104	110	110	113	118	122	125	5	5	8	13	17	20
	-3	90	91	96	100	103	105	111	112	117	121	124	126	6	7	12	16	19

18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
84	90	91	96	100	103	105	111	112	117	121	124	126	6	7	12	16	19	21
82	84	90	91	96	100	103	105	111	112	117	121	124	126	6	7	12	16	19
79	82	84	90	91	96	100	103	105	111	112	117	121	124	126	6	7	12	16
75	79	82	84	90	91	96	100	103	105	111	112	117	121	124	126	6	7	12
70	75	79	82	84	90	91	96	100	103	105	111	112	117	121	124	126	6	7
69	70	75	79	82	84	90	91	96	100	103	105	111	112	117	121	124	126	6
63	69	70	75	79	82	84	90	91	96	100	103	105	111	112	117	121	124	126
96	100	103	105	111	112	117	121	124	126	6	7	12	16	19	21	27	28	33
96	100	103	105	111	112	117	121	124	126	6	7	12	16	19	21	27	28	33
91	96	100	103	105	111	112	117	121	124	126	6	7	12	16	19	21	27	28
91	96	100	103	105	111	112	117	121	124	126	6	7	12	16	19	21	27	28
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	37	40	42	48	49	54	58	61	63	69	70	75	79	82	84	90	91	96
33	37	40	42	48	49	54	58	61	63	69	70	75	79	82	84	90	91	96
105	111	112	117	121	124	126	6	7	12	16	19	21	27	28	33	37	37	40
110	110	113	118	122	125	5	5	8	13	17	20	26	26	29	34	38	41	42
102	109	109	114	119	119	123	4	4	9	14	14	18	25	25	30	35	35	39
68	68	71	76	80	83	89	89	92	97	101	104	110	110	113	118	122	125	5
83	89	89	92	97	101	104	110	110	113	118	122	125	5	5	8	13	17	20
26	26	29	34	38	41	47	47	50	55	59	62	68	68	71	76	80	83	89
21	27	28	33	37	40	42	48	49	54	58	61	63	69	70	75	79	82	84

b) Parameters of Fuzzy Logic

Table 3 Parameters of fuzzy controller.

Fis type	Mamdani
And method	Min
Or method	Max
Implication	Min
Aggregation	Max
Defuzzification	Centroid

c) Model of Induction Machine

The model of IM in the α, β reference can be written in the following from:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = cx(t) \end{cases}$$

with

$$X = [I_{s\alpha} \quad I_{s\beta} \quad \Phi_{s\alpha} \quad \Phi_{s\beta}]^T$$

$$U = [v_{s\alpha} \quad v_{s\alpha} \quad 0 \quad 0]^T$$

$$T_r = \frac{L_r}{R_r}$$

$$\sigma = 1 - \frac{M^2}{L_s L_r}$$

$$K = \frac{M}{\sigma L_s L_r}$$

$$\lambda = [\frac{1}{T_s} + \frac{M^2}{T_r L_s L_r}]$$

$$A = \begin{bmatrix} -\frac{\lambda}{\sigma} & 0 & \frac{\sigma}{T_r}K & K w_r \\ 0 & -\frac{\lambda}{\sigma} & -K w_r & \frac{\sigma K}{T_r} \\ \frac{M}{T_r} & 0 & \frac{-1}{T_r} & -w_r \\ 0 & \frac{M}{T_r} & w_r & \frac{-1}{T_r} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$U = \begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \\ 0 \\ 0 \end{bmatrix}$$

d) Machine Parameters

The parameters of 3 phase induction machine employed for simulation purpose is given below:

Table 6 Implementation parameters.

Parameters	Values
Nominal power	1 Mw
Line to line voltage	791 V
Frequency	60 Hz
Stator resistance	0.228 Ω
Stator inductance	0.0084 H
Rotor resistance	0.332 Ω
Rotor inductance	0.0082 H
Mutual inductance	0.0078 H
Inertia	20 Kg.m^2
Friction	0.008 N.m.s
Number of poles	3

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