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A direct torque control of the induction motor based on the fuzzy logic and ANFIS controller

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Abstract: In this work, a direct torque control with 36 sectors of the induction motor (IM) drive controlled by intelligent controllers is proposed. The proposed control scheme uses the electromagnetic torque errors through an adaptive neuro-fuzzy inference system (ANFIS) and the classic PI speed controller based the fuzzy logic controller. Simulation results by using ANFIS controller and fuzzy logic are compared with those of the conventional direct torque control (DTC) with 36 sectors. The comparison results of direct torque control with intelligent controllers illustrate the reduction in the torque, THD (Total Harmonic Distortion) value of stator current and stator flux ripple and the validity of the proposed control is confirmed by the simulation results.

Keywords: *DTC, 36 sectors, IM, ANFIS controller, Fuzzy logic, THD.*

1. Introduction

Induction motors are suitable electromechanical systems for a large range of industrial applications. This is due to their high reliability, relatively low cost, and modest maintenance requirements [1]. However, IMs are considered as nonlinear, multivariable and highly coupled systems [2]. For this reason, IMs have been used especially in closed-loop for variable speed application. Even the IM is possible for high precision torque and speed command through highly preserved command method [2].

There are two most common AC drives command schemes that are being widely researched. One of it is Field Oriented Control (FOC) which was proposed by F. Blaschke. Second scheme is Direct Torque Control (DTC) which was proposed by I. Takahashi and T. Noguchi [3]. DTC provides very quick responses with simple command structure and hence, this command scheme is gaining popularity in industries. Through, DTC has high dynamic performance; it has few drawbacks such as high ripple in torque, flux, current and variation in switching frequency of the inverter [4]. In recent years, there has been great interest in multilevel inverters technology [5]. Special attention has been paid for Neutral Point Clamped inverter (NPC).

The diode clamped multilevel inverter has been used in AC drives over the last decade. It uses clamping diodes and a group of cascaded DC capacitors to achieve multiple levels in the inverter output voltage for the reduction of dv/dt and THD. The diode clamped inverter also features high operating voltage without switching devices in series [6]. The inverter can be configured as a three-, four-, or five-level topology,...etc, in this paper we used five-level NPC inverter.

By utilizing the multilevel inverter in DTC scheme, the choices of voltage vectors that can be used to control the torque and flux are increased [7]. On the other hand, the multilevel direct torque control of electrical drives has become an attracting topic in research and academic community over the past decade [8]. This paper proposes a novel scheme of 36 sectors DTC command to improve the drive performance. Intelligent direct torque control with five-level NPC inverter is used to improve dynamic response performance and decrease the torque ripple and THD value of stator current.

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2. DTC Control with 36 sectors

The principle of DTC is decoupled and simultaneous control of torque and stator flux is achieved by direct adjustment of the stator voltage, in accordance with the torque and flux errors, without intermediate current control and/or decoupling network. The instantaneous values of flux and torque are calculated from measured variables (voltage and currents) and then directly controlled by selecting optimum inverter switching modes so that the required optimum voltage vector is generated [9]. DTC is the first technique to control the "real" motor control variable of torque and flux [10]. The Figure. 1 show the schematic of the basic functional blocks used to implement the DTC of induction motor drive [11].

The stator flux can be evaluated by integrating from the stator voltage equation [12]:

$$\Phi_S = \int_0^t \left(V_S - R_S \cdot i_S\right) dt \tag{1}$$

The magnitude of the stator flux can be estimated by:

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

The stator flux sector is determined by the components $\Phi_{s\alpha}$ and $\Phi_{s\beta}$. The angle between the referential and Φ_S is equal to [4]:

$$\theta = arctg\left(\frac{\Phi s\beta}{\Phi s\alpha}\right) \tag{3}$$

Torque can be calculated using the components of the estimated flux and measured currents:

$$Te = \frac{3}{2} p\left(\Phi_{s\alpha}\, is\beta - \Phi_{s\beta}\, is\alpha\right) \tag{4}$$

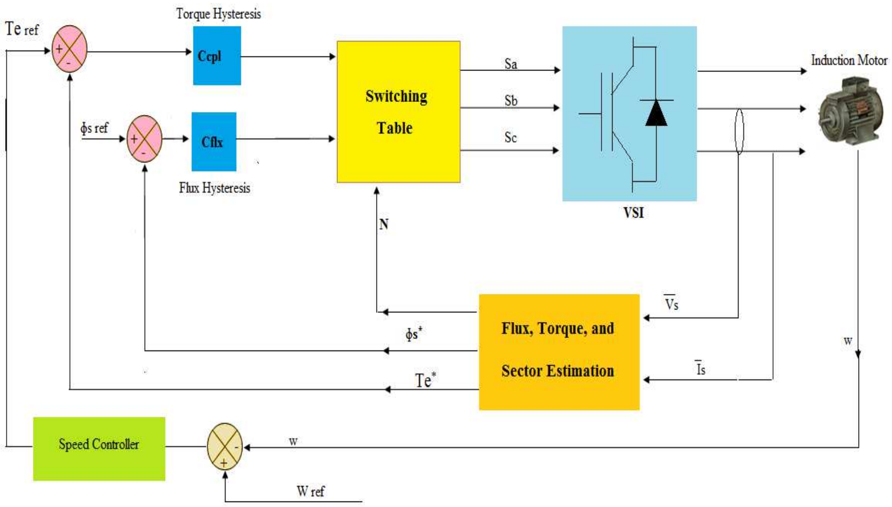


Figure. 1 Conventional DTC control of IM drives.

2.1 Five-Level NPC Inverter

Multilevel inverters are an alternative to traditional two-level and three-level inverters. These inverters allow you to convert the electrical energy provided by direct current sources, such as batteries or solar panel banks, into an ideal alternating current of sine wave form whose parameters (amplitude, frequency) can be fixed or variable [13]. Multilevel inverters have the advantages of overcoming voltage limit capability of semiconductor switches, and improving 2 harmonic profiles of output waveforms [8]. The NPC topology has been constructed by higher number of power switches so thus additional control scheme required. DC link neutral point clamping is need for maintaining balanced voltage [2].

By using a multilevel inverter in the classical DTC scheme of IM, a more precise control of torque and flux can be achieved from extra flexibility in selecting the optimum voltage vector [14]. Figure. 2 shows the circuits of a five-level diode clamped inverter [15]. Each leg is composed of four upper and lower switches with ant-parallel diodes. Four series DC-link capacitors split the DC-bus voltage in half. 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 shorted be continuous [16]. Each leg of the inverter can have five possible switching states; 4, 3, 2, 1 or 0.

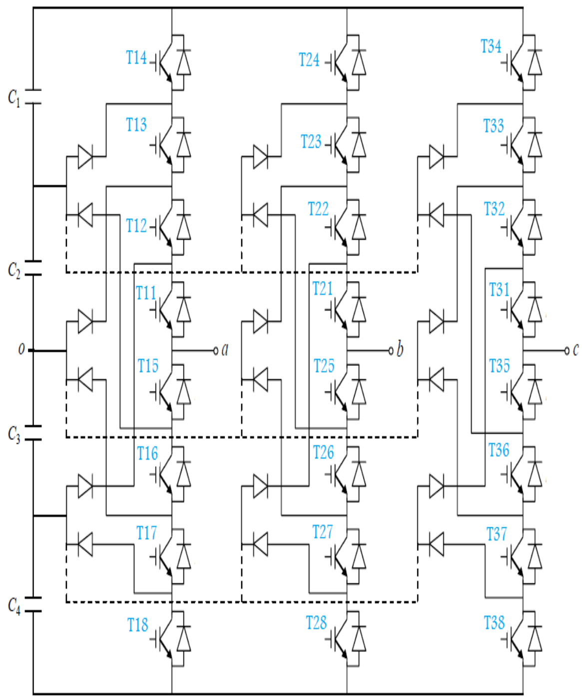


Figure. 2 Schematic diagram of a five-level inverter.

A five-level voltage inverter can achieve 60 separate positions in the phase corresponding to the 61 sequences of the voltage inverter. The representation of the space voltage vectors of a five-level NPC inverter for all switching states is given by Figure. 3 [17].

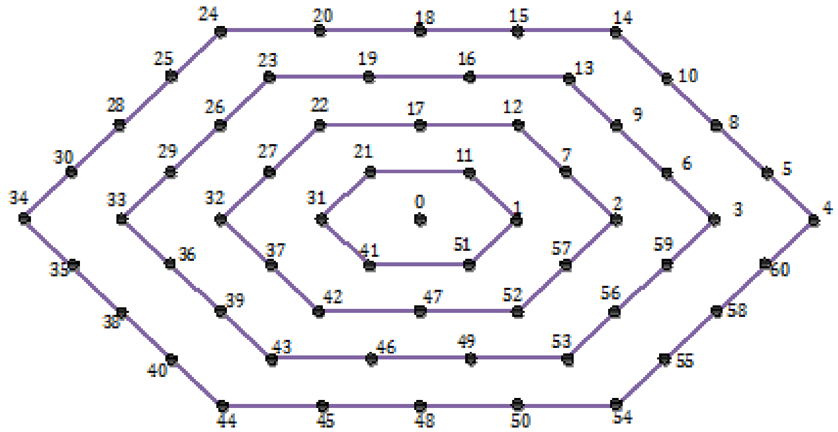
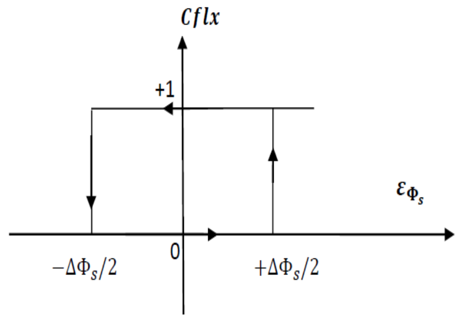


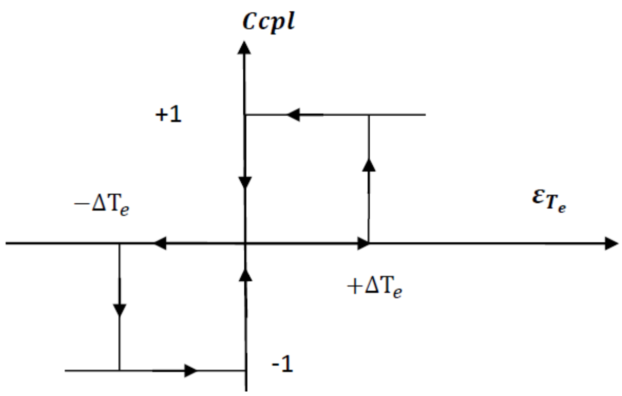
Figure. 3 Space vector diagram of five-level inverter.

2.2 Switching Table of Five-Level DTC Control

Two-level stator flux and three-level torque hysteresis controllers (Figure. 4) are used according to the outputs of the torque controller and the sector information, appropriate voltage vectors for both the inverters are selected from a switching table as it is shown in Table 1.



a) Stator flux comparator



b) Three-level torque comparator.

Figure. 4 Hysteresis comparators.

Table 1. Proposed switching Table of five-level inverter

N	Cflx					
	1			0		
	Ccpl					
	1	0	-1	1	0	-1
1	14	2	54	24	32	44
2	15	2	55	25	32	45
3	18	2	58	28	32	48
4	18	7	58	28	37	48
5	20	7	60	30	37	50
6	24	7	4	34	37	54
7	24	12	4	34	42	54
8	25	12	5	35	42	55
9	28	12	8	38	42	58
10	28	17	8	38	47	58
11	30	17	10	40	47	60
12	34	17	14	44	47	4
13	34	22	14	44	52	4
14	35	22	15	45	52	5
15	38	22	18	48	52	8
16	38	27	18	48	57	8
17	40	27	20	50	57	10
18	44	27	24	54	57	14
19	44	32	24	54	2	14
20	45	32	25	55	2	15
21	48	32	28	58	2	18
22	48	37	28	58	7	18
23	50	37	30	60	7	20
24	54	37	34	4	7	24
25	54	42	34	4	12	24
26	55	42	35	5	12	25
27	58	42	38	8	12	28
28	58	47	38	8	17	28
29	60	47	40	10	17	30
30	4	47	44	14	17	34
31	4	52	44	14	22	34
32	5	52	45	15	22	35
33	8	52	48	18	22	38
34	8	57	48	18	27	38
35	10	57	50	20	27	40
36	14	57	54	24	27	44

3. DTC with Intelligent Controllers

The principle of 36 sectors DTC control with intelligent controllers is similar to conventional DTC with five-level NPC inverter. The difference is using an adaptive neuro-fuzzy inference system (ANFIS) controller to replace the torque hysteresis loop controller and fuzzy logic controller. As shown in Figure. 5. The main objective of this study is the reduction of electromagnetic torque ripples, stator flux ripples and THD value of stator current.

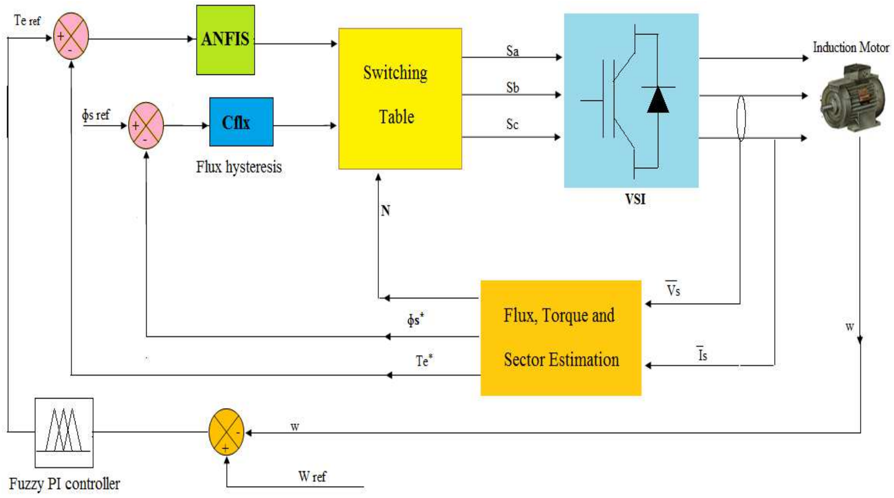


Figure. 5 DTC with intelligent controllers.

3.1 Design of Fuzzy Speed Controller

In the objective to control the static error and to reduce the time response while preserving the system stability, the proportional integral corrector PI used is replaced with a fuzzy logic controller [18]. The fuzzy control is basically nonlinear and adaptive in nature, giving robust performance under parameter variation and load disturbance effet [19].

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 [20]. The fuzzy controller design is based on intuition and simulation. These values compose a training set which is used to obtain the table rules [21]. The block diagram of the fuzzy logic speed controller is shown in Figure. 6.

On 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 [22, 23], and gives the change of the output of fuzzy logic controller in terme of two input: the error ($e=w_{ref} - w$) and change of error (Δe).

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

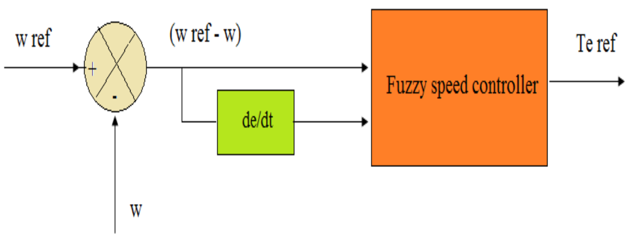


Figure. 6 Fuzzy logic control of speed.

3.2 Design of ANFIS Torque Hysteresis Comparator

The ANFIS controller combines fuzzy logic and artificial neural networks to evaluated the reference voltage required to drive the flux and torque to the demanded values within a fixed time periode [24]. The ANFIS is a class of adaptive multilayer feed-forward network that is functionally equivalent to a fuzzy inference system. Each neuron in the ANFIS applied a particular function on incoming signals as well a set of parameters relating to the neuron. To identify the adaptive network parameters, this fuzzy inference method employs a hybrid learning algorithm which combines the gradient method and least squares estimate (LSE). Not only can this hybrid learning algorithm guarantees to find global minima, but it also decreases the convergence time of the network due to decreasing dimensions of research space in the gradiant method [25].

In this paper, the ANFIS controller of torque hysteresis for five-level DTC with 36 sectors was developed. The Adaptive Neuro-Fuzzy inference system is developed using Matlab. The block diagram for ANFIS based torque hysteresis controller is shown in Figure. 7.

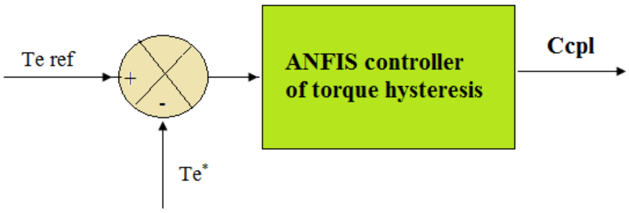


Figure. 7 ANFIS control of torque hysteresis controller.

Then the designed ANFIS has two inputs namely, the reference torque and estimated torque while the output is the Ccpl (Torque hysteresis controller). The structure of ANFIS torque controller is shown in Figure. 8.

The developed fuzzy rules (7×7) are included in the ANFIS controller and are not shown here for the sake of convenience. The control decisions are made based on the fuzzified variables in the Table. 2. The inference involves a set of rules for determining the output decisions. As there are 2 input variables and 7 fuzzified variables, the controller has a set of 49 rules for the ANFIS controller. Out of these 49 rules, the proper rules are selected by the training of the neural network with the help of back propagation algorithm and these selected rules are fixed. Further, it has to be converted into numerical output, i.e., they have to be de-fuzzified.

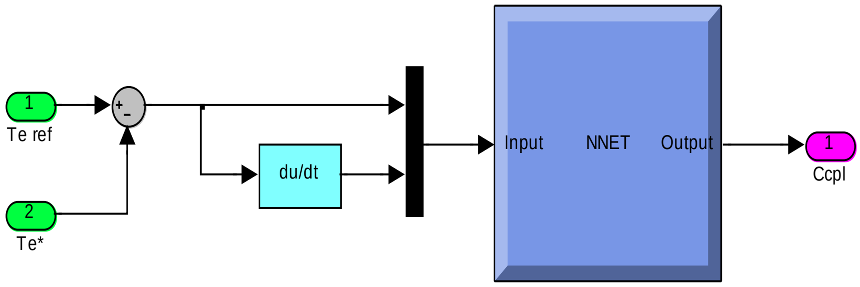


Figure. 8 ANFIS structure for torque hysteresis comparator.

4. Results

The simulations of the five-level DTC with intelligent controllers of induction motor drive are compared with classical DTC with five-level inverter. A 3-phase, 3 pole, induction motor with parameters of Rs=0.228Ω, Rr=0.332Ω, Ls=0.0084H, Lr=0.0082H, Lm=0.0078H, J=20 Kg.m2 are considered**.**

The performance analysis is done with stator current, stator flux and torque plot. The dynamic performance of the conventional five-level DTC control with induction motor is shown Figure. 9. The

dynamic performance of the five-level DTC control with intelligent controllers (ANFIS controller of torque hysteresis and fuzzy speed controller) is shown Figure. 10.

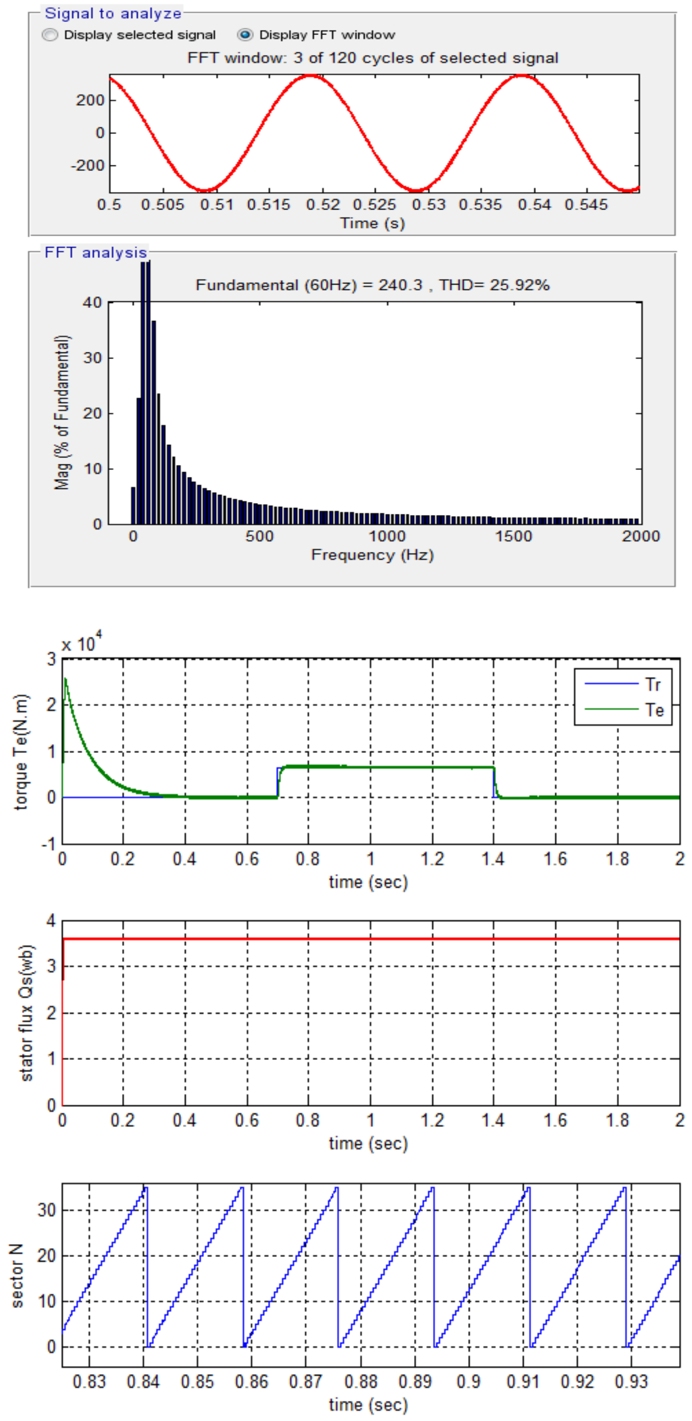


Figure. 9 Dynamic responses of conventional DTC with five-level inverter for IM.

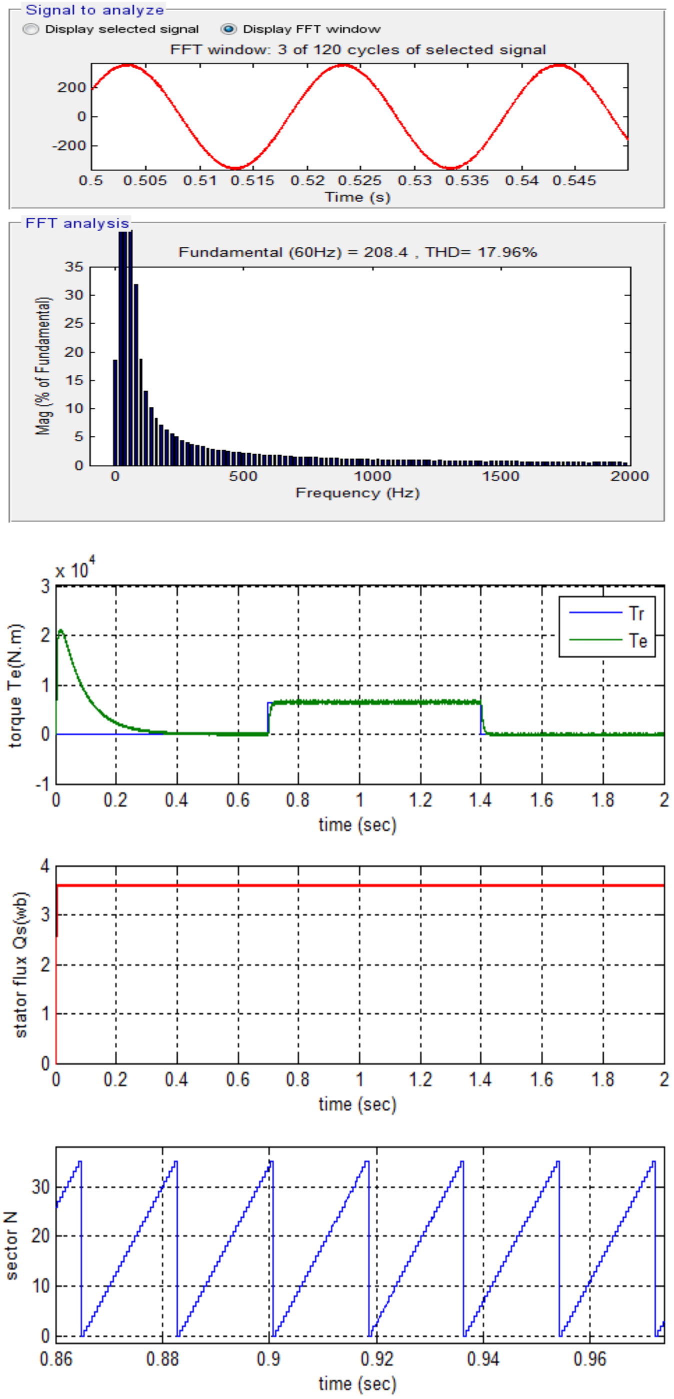


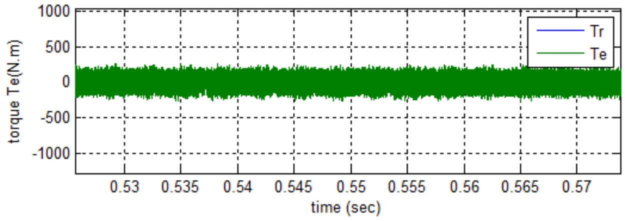
Figure. 10 Dynamic responses of five-level DTC with intelligent controllers for IM.

From the simulation results presented in Figures. 9-10 it is apparent that the THD value of stator current for the five-level DTC with intelligent controllers (ANFIS and fuzzy logic) is considerably reduced. Table 3 shows the comparative analysis of THD value for stator current.

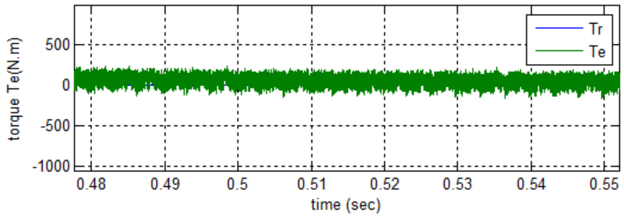
Table 3. Comparative analysis of THD value

Conventional five-level DTC	Five-level DTC with intelligent controllers
25.92%	**17.96%**

Figure. 11(a) shows torque ripples for conventional DTC with five-level inverter have a large value of ripple, while Figure. 11(b) shows torque ripple for 36 sectors DTC with intelligent controllers (ANFIS and fuzzy logic controllers) which has a minimum value of ripple.



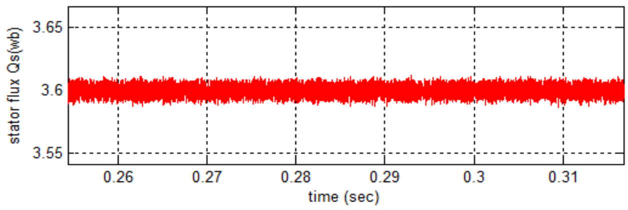
a) Conventional DTC with five-level inverter



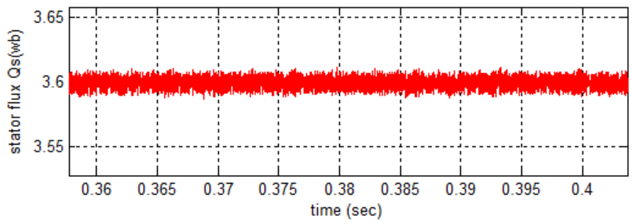
b) DTC with intelligent controllers

Figure. 11 Zoom in the torque.

Figure. 12 shows the stator flux responses of both the conventional and five-level DTC with intelligent controllers. It is found that the proposed DTC scheme exhibits smooth response and lesser ripple in the stator flux as compared to the conventional five-level DTC scheme.



a) Conventional DTC with five-level inverter



b) DTC with intelligent controllers

Figure. 12 Zoom in the stator flux.

5. Conclusion

In this paper, we proposed intelligent controllers for torque hysteresis and speed controller of induction motor controlled by five-level DTC with 36 sectors. Using intelligent controllers (ANFIS and Fuzzy logic) reduces the THD value of stator current, torque ripple and stator flux ripple of induction motor performance compared to obtain with a classical controller (classic PI and torque hysteresis controller). The simulation results obtained were satisfactory, and system stability has been insured.

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