Torque ripple reduction in Direct Torque Control of induction motor using double fuzzy logic control

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***Abstract*— This paper shows the application of fuzzy logic technique based on duty ratio control and contribution of fuzzy logic control to select optimum voltage vector to reduce the ripple in torque in an induction motor. The hybrid technique is used to get the best results over than classic direct torque control (C_DTC). The conventional proportional & integral (PI) control is used to make regulation for speed. Using MATLAB/SIMULINK software, simulation has been made to illustrate this strategy and compare the results of two ways.**

Keywords— Induction motor drive; Direct Torque Control (DTC) ; double fuzzy logic control; Voltage Vector Fuzzy Controller; Duty ratio fuzzy logic control.

I. Introduction

Induction machines are widely used in most of industry field because it's rugged, cheap, simple and easy for maintenance. However the difficult of control of it was the biggest problem until the high power switching devices and fast microprocessors are appeared. Which makes it is possible to control in the induction machine to give fast response, high performance and high efficacy [1].

Nowadays, the induction machine is controlled by using many strategies. One of these strategies is direct torque control (DTC). Since it has several of merits such as easy for implementation, high performance (etc). But the biggest disadvantages of this strategy are the high ripple torque. In order to reduce this ripple there are many techniques and one of them is fuzzy logic control [2].

Fuzzy logic was introduced to control in nonlinear system. So that it was chosen to reduce the torque ripple in DIRECT TORQUE CONTROL [3].

II. Classic DTC System of Induction Motor

In direct torque control strategy, the proper selected voltage vector is directly chosen from the table according to the need of increasing or decreasing the torque and the flux as shown in figure 1.To determine stator vector voltage to be applied, we begin by dividing the circular trajectory of the stator flux into six symmetrical sectors referred as the inverter voltage vectors. In Fig.1the d-axis represent the stator flux and the q-axis represent the torque. By applying the voltage vector (v2) the torque and the flux will be increased at first sector. On the other hand if the voltage vector (v5) is applied both the torque and the flux will be decreased. Then, after studying the effect of each stator vector voltage both the flux and torque can be directly controlled. That is done by using three and two levels comparator for torque and flux respectively.

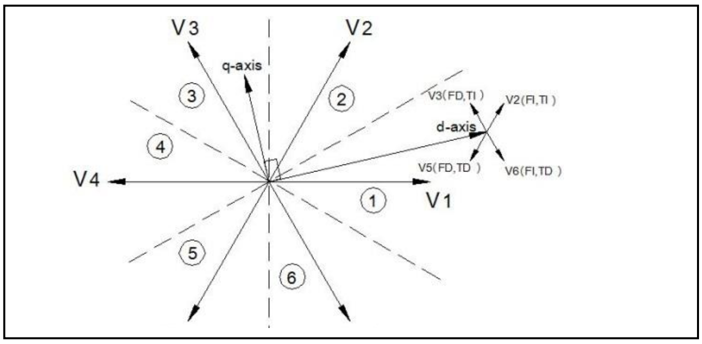

Fig. 1. *voltage select strategy for C_DTC.*

Table 1 demonstrates the voltage vector according to Fig. 1. As known in DTC whenever the switching frequency increase the ripple of torque will be decreased. To get a small ripple the switching frequency will be very high; but this lead to increase the losses in switching devices also the cost will be increase [1, 4].

TABLE I. Classic DTC System of Induction Motor

Flux Error	Torque Error	s1	s2	s3	s4	s5	s6
FI	TI	V2	V3	V4	V5	V6	V1
	T=	V0	V7	V0	V7	V0	V7
	TD	V6	V1	V2	V3	V4	V5
FD	TI	V3	V4	V5	V6	V1	V2
	T=	V7	V0	V7	V0	V7	V0
	TD	V5	V6	V1	V2	V3	V4

Fig. 2shows the block diagram of a DTC-based induction machine drive combined with an IP speed controller.

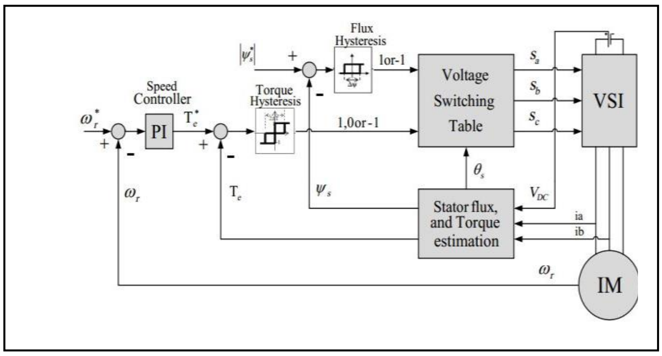

Fig. 2. *Direct Torque Control combined with speed controller*

Mathematical model for flux estimator based on stator parameter

The stator flux linkage is given by :

$$\varphi_{sd} = \int_0^t (V_{sd} - R_s i_{sd})dt \quad (1)$$

$$\varphi_{sq} = \int_0^t (V_{sq} - R_s i_{sq})dt \quad (2)$$

$$\varphi_s = \sqrt{\varphi_{sd}^2 + \varphi_{sq}^2} \quad (3)$$

$$\theta = \tan^{-1}(\varphi_{sd}/\varphi_{sq}) \quad (4)$$

Electromagnetic torque for the induction machine can be determined from:

$$T_{em} = \frac{3}{2} p|\varphi_s||i_s| \sin\alpha \quad (5)$$

Where: α Is the angle between the stator flux-linkage and stator-current space vector.

III. Direct Torque Control of induction motor using double fuzzy logic control

A. Fuzzy Logic Control (FLC)

The intelligent techniques like fuzzy logic control have advantages such as:

- FLC don't need exact mathematical model.
- FLC can handle nonlinear and complex system.
- FLC is based on linguistic rules and this can be easy implemented by software and digital signal processor (DSP) [5].

The whole system consists of classic PI control for speed regulation, voltage vector fuzzy control, and duty ratio control using fuzzy system, voltage and current sensors.

At first the fuzzy control system will select the optimum voltage vector. After that the second fuzzy system will calculate the proper duty ratio; and by this way we can combine with this double fuzzy system and this will be explained later. After that the classic pI speed regulation will calculate the torque reference to keep the speed constant at the input reference speed [2, 6].

1) Voltage Vector Fuzzy Controller

In the conventional DTC the selection of voltage vector depends on the two discrete hysteresis comparators, one for the torque with three level and the other for the stator flux with two level and because of the range of selection is too small, the system may be select the same voltage vector and this lead to increase the torque ripple and to overcome on this problem the fuzzy logic control will be responsible for the voltage vector selection.

We can replace the strategy of the selection of voltage vector and the table of selection with fuzzy rules. The fuzzy input sets is dt (torque ripple), df(stator flux error), and θ (stator flux angle); and the fuzzy output $(v_1, v_2, \dots, v_7)$.The defuzzyfcation method to give the optimum voltage vector is MOM(middle of maximum)[5,7,8] . The Fuzzy rules can be obtained from the Table 2.

TABLE II. Fuzzy Logic-Switcher Rules

df	dt	θ1, θ7	θ2	θ3	θ4	θ5	θ6
P	P	V5	V6	V1	V2	V3	V4
	Z	V7	V7	V7	V7	V7	V7
	N	V3	V4	V5	V6	V1	V2
N	P	V6	V1	V2	V3	V4	V5
	Z	V7	V7	V7	V7	V7	V7
	N	V2	V3	V4	V5	V6	V1

The membership functions of the FLC are given in Fig. 3.

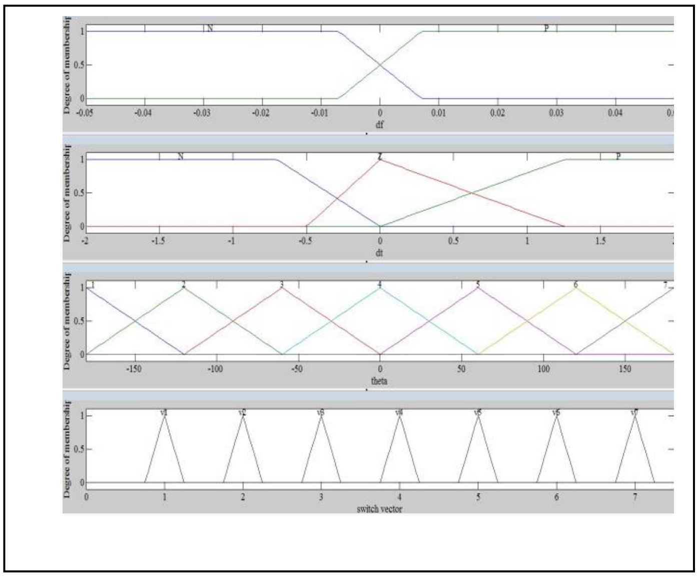

Fig. 3. *The membership functions of the switching vector*

2) Duty Ratio Control

In the conventional DTC a voltage vector is applied for the entire switching period and in this case the torque ripple unable to be controlled over this switching period and to decrease the torque ripple the switching frequency must be increase and this need faster control and switching devices. Therefore, the costs of the controller and the inverter will increase.

By dividing the switching period to two parts we can select another voltage vector and by this way the torque ripple can be controlled and reduced and this achieved by using duty ratio control and Fig. 4 shows that. Since the duty ratio during each switching state is a nonlinear function for this reason we use the FLC to determine the optimum duty ratio for every cycle [4,6,8,9].

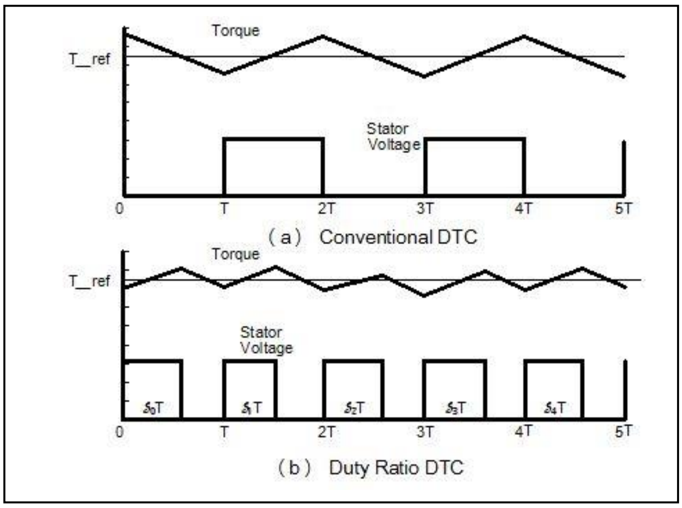

Fig. 4. *Effect of the duty ratio control on the torque ripple*

The fuzzy input are torque error, and flux position, and the output is the duty ratio and the Defuzzification method is COG(Center of Gravity). The fuzzy rule is shown in Table 3 and its content of two groups of which contains nine rules.

TABLE III. RULES FOR THE DUTY RATIO FUZZY CONTROLLER

dF	**dT / Flux angle**	***Small***	***Medium***	***Large***
Negative	***Small***	Small	Small	Medium
	Medium	Small	Medium	Large
	Large	Small	Medium	Large
Positive	***Small***	Small	Medium	Large
	Medium	Small	Medium	Large
	Large	Medium	Large	Large

The first group is used when the stator flux linkage is smaller than its reference value and the second group of rules is used when it is greater than its reference value. We can select between the two groups and that by knowing the previous and the next voltage vector according to Table 4.

TABLE IV. FLUX AND TORQUE VARIATION ACCORDING T APPLIED VOLTAGE VECTOR

VOLTAGE *VECTOR*	***INCREASE***	***DECREASE***
Stator Flux	V_K, V_{K+1}, V_{K-1}	$V_{K+2}, V_{K-2}, V_{K+3}$
Torque	V_{K+1}, V_{K+2}	V_{K-1}, V_{K+2}

The membership functions of the FLC are given in Fig. 4.

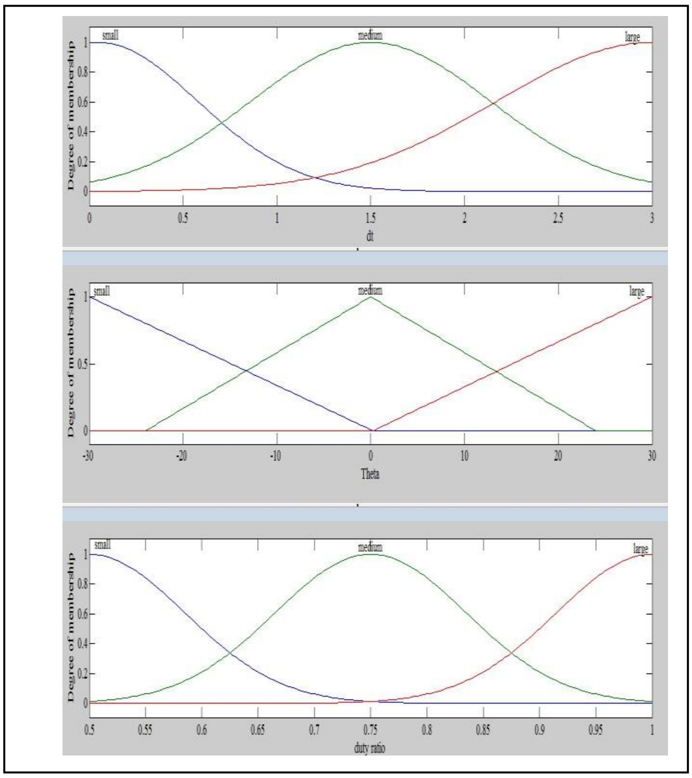

Fig. 5. *The membership functions of the duty ratio*

IV. Simulation Results

To study the performance of the fuzzy logic controller with direct torque control strategy, the simulation of the system was conducted by using MATLAB /SIMULINK and fuzzy logic tools. The parameters of induction motor as Table 5.

TABLE V. RULES FOR THE DUTY RATIO FUZZY CONTROLLER

Rated voltage	460 V
Pole pairs	2
Stator resistance	1.115
Stator inductance	5.97 mH
Rotor resistance	1.083
Rotor inductance	5.97 mH
Mutual inductance	207 mH

A. At first the classic DTC is implemented at defrent switching frequencies (10K, 20K) and the whole system as shown in Fig. 6.

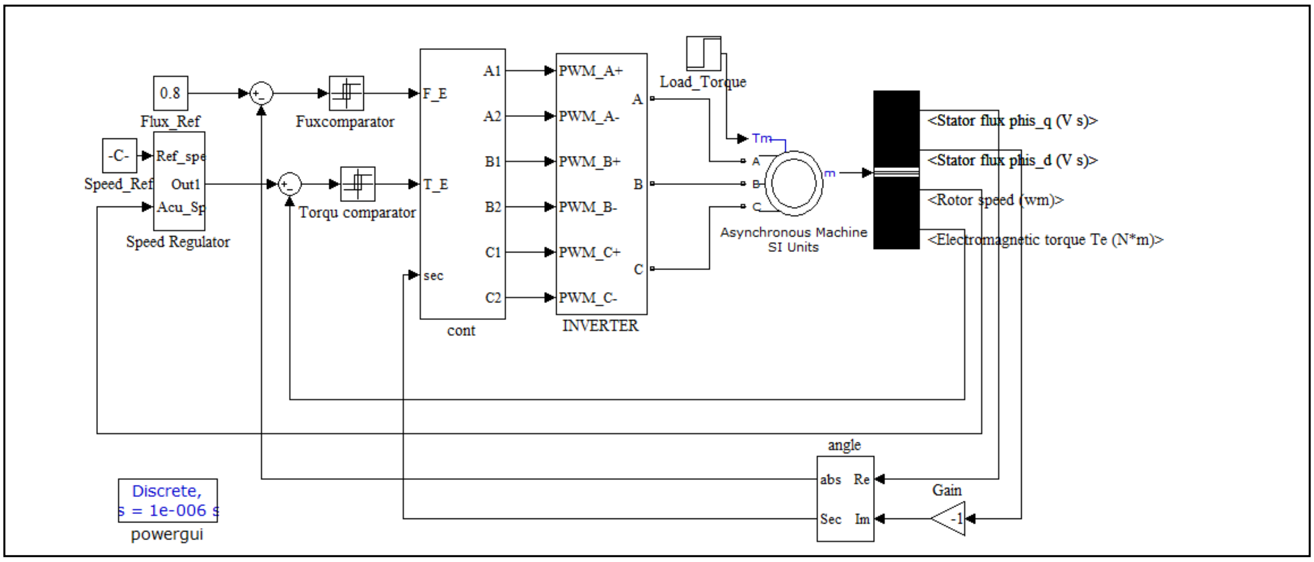

Fig. 6. *A direct torque control scheme for IM motor drives*

The dynamic responses of flux and torque with a constant command flux of 0.8Wbs with switching frequancy (10 and 20k) are shown in Fig. 7 to 10 respectively. A load torque is insured. After t=3.5s to study the performance of the different controllers.

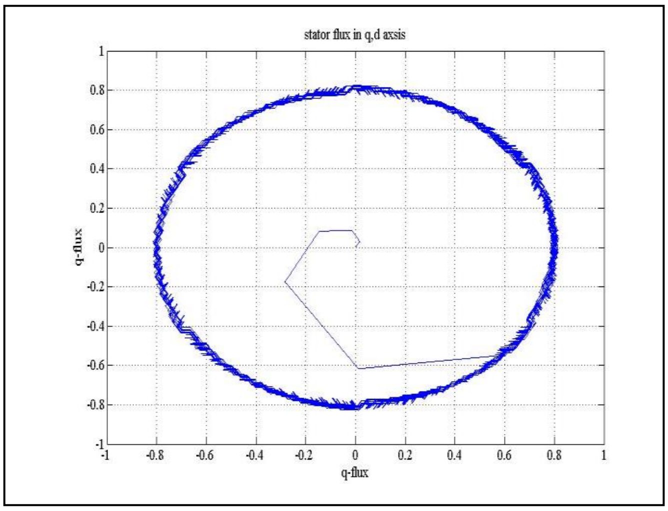

Fig. 7. *Stator flux response with 10k switching frequancy*

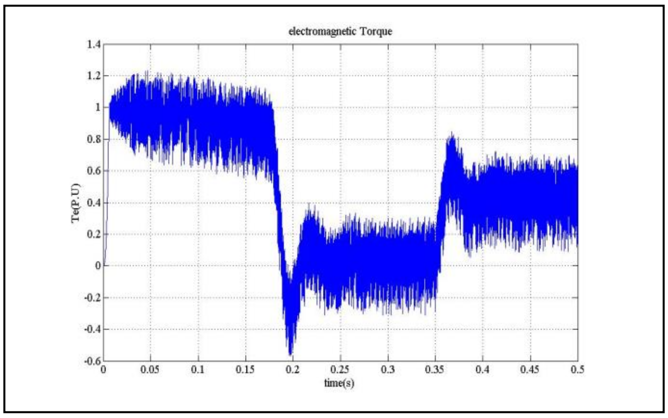

Fig. 8. Electromagnetic torque response with 10k switching frequancy

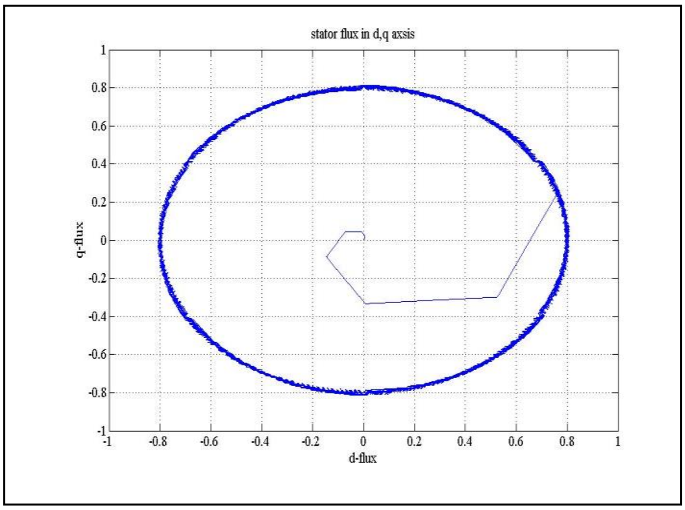

Fig. 9. *Stator flux response with 20k switching frequancy*

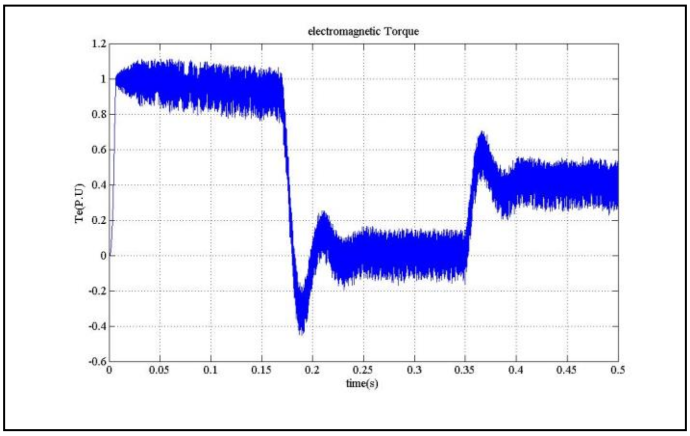

Fig. 10. Electromagnetic torque response with 20k switching frequancy

B. By using double fuzzy logic, it is possible it is possible to perform a fuzzy logic based Duty Ration Control where optimum duty ratio is selected for each switching time, and the voltage vector can be selected every switching cycle. The whole system as shown inFig .11.

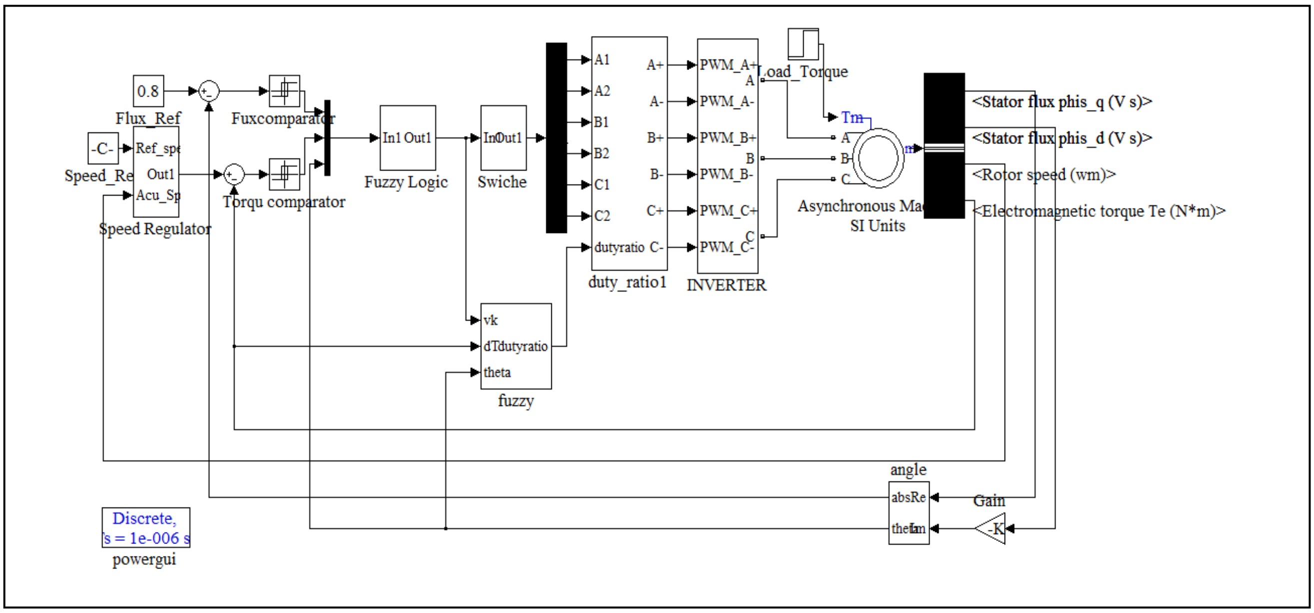

Fig. 11. *Double fuzzy logic system*

Th dynamic responses of flux and torque by using double fuzzy logic system at switching frequency (10k) with the same load torque and flux as in C_DTC are shown in figures (12, 13) respectively.

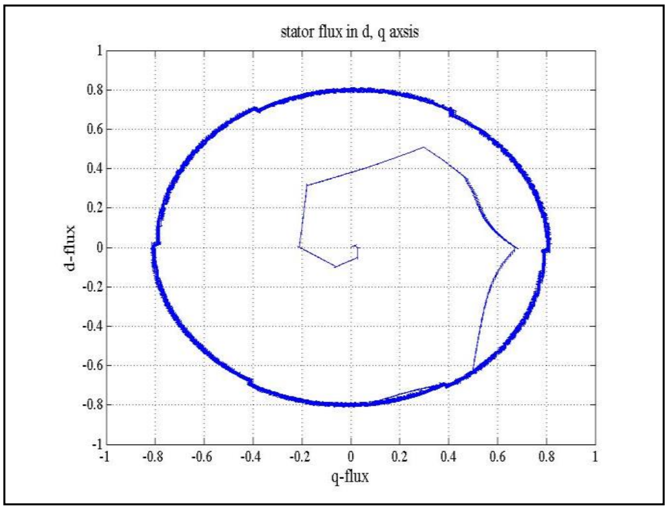

Fig. 12. *Stator flux response using double fuzzy system*

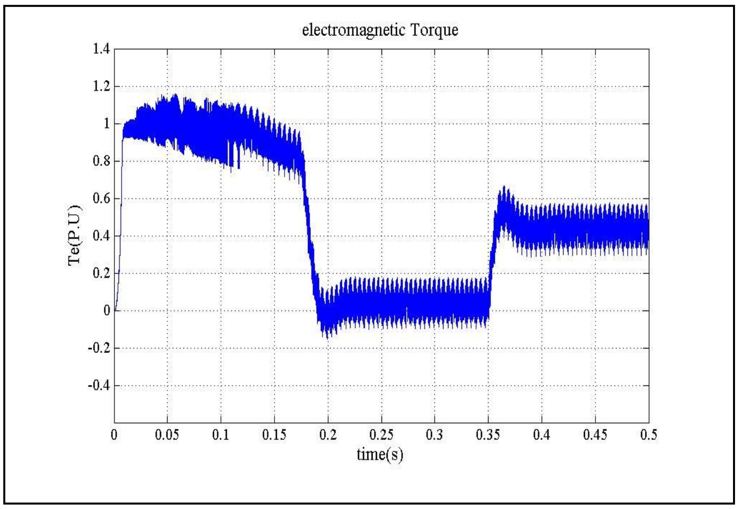

Fig. 13. Electromagnetic torque response using double fuzzy system

V. Conclusion

In this paper, we presented the DTC with both its classical version and by using fuzzy logic control. This contribution of fuzzy logic improves the torque ripple over than DTC at the same switching frequency. The double fuzzy logic systems are used to perform this task. The first fuzzy logic is responsible for the selection of voltage vector switch according to look up table for C-DTC. We can change the rule of selection by using twelve sectors look up table, change the membership functions and change the rule of duty ratio calculation to give better result. From simulation results it is obvious that the torque ripple using fuzzy logic control less than classic control as shown in Table 6.

TABLE VI. COMPARISON IN TORQUE RIPPLE BETWEEN TWO METHODS.

Control method	*C-DTC switching frequency (10k Hz)*	*C-DTC switching frequency (20k Hz)*	*DTC using Fuzzy Logic switching frequency (10k Hz)*
Torque Ripple (P.U)	0.6	0.4	0.3

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