DOI: 10.21917/ijsc.2011.0034

PERFORMANCE ENHANCEMENT OF DIRECT TORQUE CONTROL OF INDUCTION MOTOR USING FUZZY LOGIC

P. Sweety Jose[1], Jovitha Jerome[2] and S. Sathya Bama[3]
Department of Electrical and Electronics Engineering, PSG College of Technology, Tamil Nadu, India
E-mail: [1]psj@eee.psgtech.ac.in, [2]jjovitha@yahoo.com and [3]sathyabama.sekar@gmail.com

Abstract
DTC is strategy of selecting proper stator voltage vectors to reduce torque error and flux error. DTC uses hysteresis band controller whose control action has no difference between large torque error and small one. This results in high torque ripple. In order to reduce the torque ripple and to improve the performance of DTC, DTC based on Fuzzy Logic is proposed in this paper. The simulations are carried out using MATLAB and comparison is made between conventional DTC and DTC using Fuzzy Logic and simulated results are shown.

Keywords:
DTC, Fuzzy Logic, Induction Motor, Switching Table

1. INTRODUCTION

For high power industrial applications it is desirable to use AC motor drive instead of DC. But due to inherent torque coupling present in AC motor the dynamic response becomes sluggish. In order to improve the performance of AC motor we follow motion control techniques so that AC the motor can provide good dynamic torque response as it is obtained from dc motor drives. Many control schemes have been proposed for this purpose, among which vector control needs quite complicated to on line coordinates transforms to decouple interaction between flux control and torque control in order to provide fast control of induction motor.

In recent years an advanced control method called direct torque control has gained importance owing to its capability to produce fast torque control of induction motor. Although in these systems such variables as torque, flux modulus and flux sector are required, resulting DTC structure is particularly simplistic. Conventional DTC does not require any mechanical sensor or current regulator and coordinate transformation is not present, thus reducing the complexity. Fast and good dynamic performances and robustness [6] has made DTC popular and is now used widely in all industrial applications. Despite these advantages it has some disadvantages such as high torque ripple and slow transient response to step changes during start up. The reason for torque ripple in DTC is because of hysteresis controller for stator flux linkage and torque. The ripples can be reduced if the errors of the torque and the flux linkage and the angular region of the flux linkage are subdivided into several smaller subsections[4]. Since the errors are divided into smaller sections different voltage vector is selected for small difference in error so a more accurate voltage vector is selected and hence the torque and flux linkage errors are reduced. For this purpose we follow artificial intelligent techniques such as neural network, Fuzzy Logic.

In this paper the Fuzzy Logic (FL) method, which is based on the language rules, is employed to solve this nonlinear issue.

2. DIRECT TORQUE CONTROL

The direct torque control technique involves the estimation of torque and flux from voltage and current. On the basis of the errors between the reference and the estimated values of torque and flux it is possible to directly control the inverter states in order to reduce the torque and flux errors within the prefixed band limits. Direct torque control is a strategy research for induction motor speed adjustment fed by variable frequency converter.

Electromagnetic torque in 3-phase Induction Motor can be expressed as:

$$t_e = \frac{3}{2} \quad - \quad \frac{Lm}{LrLs'}|\Psi_r|\,|\Psi_s| \sin\gamma \tag{1}$$

where, Ψs = stator flux
Ψr = stator flux
γ = angle between stator and rotor flux

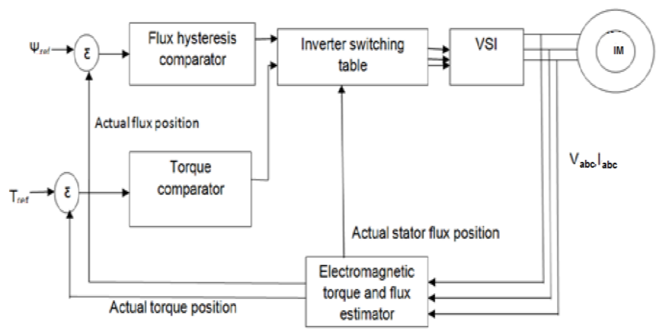

Fig.1. Conventional direct torque control

If stator flux modulus is kept constant and its angle is changed, quickly then electromagnetic torque is directly controlled. The reference values of stator flux modulus and torque are compared to their actual values [11]. The resulting errors are fed to the input of optimum switching table. The basic principle of DTC is to directly manipulate the stator flux vector such that the desired torque is produced. This is achieved by choosing an inverter switch combination that drives the stator flux vector by directly applying the appropriate voltages to the motor windings.

Vector model of inverter output voltage:

In a three phase voltage source inverter, the switching commands of each inverter leg are complementary. For each leg a logic state C_i (i=a, b, c) is defined, that is C_i is 1 if the upper switch is turned on and lower switch is turned off. If C_i is 0 then it means that the lower switch is on and upper switch is turned off. Since three are 3 independent legs there will be eight different states, so eight different voltages [2][3][5]. Fig.2 shows the three phase inverter fed from a dc source.

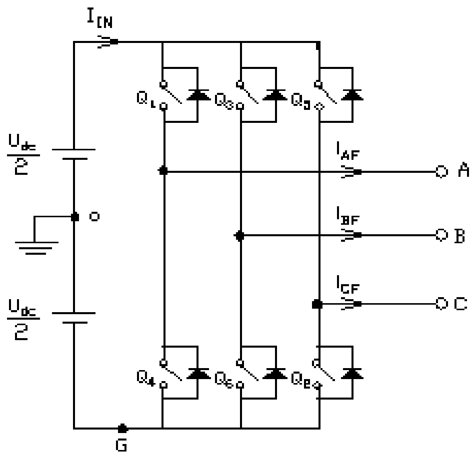

Fig.2. Three phase voltage inverter

To study the performance of the developed DTC model, a closed loop torque control of the drive is simulated using Matlab/Simulink simulation package. The torque error and flux errors are compared in their respective defined hysteresis band to generate the respective logic states as S_T and S_Ψ. The sector determination logic state S_θ is used as the third controlling signal for referring the DTC switching table. These three controlling signals are used to determine the instantaneous inverter switching voltage vector from three-dimensional DTC switching lookup table. The simulation results are implemented for conventional DTC scheme and proposed Fuzzy based DTC scheme. There are six non-zero voltage vectors and two zero voltage vectors which is shown in Fig.3 [9].

Table.1. Stator Flux Switching Sector

θ_{fs}	Sextant
$0 < \theta_{fs} < \pi/3$	<2>
$-\pi/3 < \theta_{fs} < 0$	<3>
$-2\pi/3 < \theta_{fs} < -\pi/3$	<4>
$-\pi < \theta_{fs} < -2\pi/3$	<5>
$2\pi/3 < \theta_{fs} < \pi$	<6>
$\pi/3 < \theta_{fs} < 2\pi/3$	<1>

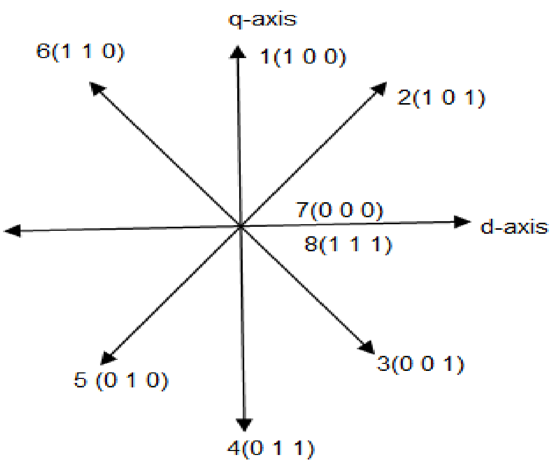

Fig.3. Partition of d, q plane in six angular sectors

The stator flux linkage space vector can be expressed as,

$$\Psi_s = \int (V_s - R_s i_s)\, dt \quad (2)$$

Neglecting the stator ohmic drop, we have

$$\frac{d\Psi s}{dt} = (V_s - R_s I_s)\, dt \quad (3)$$

$$\frac{d\Psi s}{dt} = V_s \quad (4)$$

Then, in a short interval of time Δt, we have

$$\Delta\psi_s = V_s * \Delta t \quad (5)$$

where, Vs is one of the eight voltage vectors of the six pulse inverter. By applying appropriate non-zero voltage vector, the stator flux can be rotated in any direction quickly and by applying the zero voltage vector the flux rotation can be stopped [4].

Stator flux and torque estimation:

The magnitude of stator flux can be estimated as follows [2].

$$\Psi_{sd} = \int (V_{sd} - R_s i_{sd})\, dt \quad (6)$$

$$\Psi_{sq} = \int (V_{sq} - R_s i_{sq})\, dt \quad (7)$$

The developed torque of the motor is computed from these d-q axis flux and current components. The torque component is calculated by means of equation,

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)[i_{sq}\,\psi_{sd} - i_{sd}\,\psi_{sq}] \quad (8)$$

The calculated magnitude of stator flux and electric torque are compared with their reference values in their corresponding hysteresis comparators. The hysteresis controller compares the calculated value with the reference value and generates error signal. The hysteresis controller constraints the torque and flux within its band and controls the torque and flux value [3].The torque and flux error along with the position of stator flux is given as input to DTC switching table which outputs the corresponding voltage vector which decides the switching logic of the gate of the inverter [7]. Thus the inverter voltage applied to the motor varies corresponding to the changes in torque demand, thereby controlling the torque. The appropriate selection of voltage vector depends on the torque error, flux error and stator flux position. According to the concept of DTC the voltage vector selected should be such that it reduces the torque and flux error. The sector estimation from stator flux angle is given in Table.1. Switching table for DTC is shown in Table.2 [2][3].

Table.2. Switching Table for DTC

S_ψ	S_T	S_θ					
		<1>	<2>	<3>	<4>	<5>	<6>
1	1	110	100	101	001	011	010
1	0	111	000	111	000	111	000
1	-1	101	001	011	010	110	100
0	1	010	110	100	101	001	011
0	0	000	111	000	111	000	111
0	-1	001	011	010	110	100	101

3. PRINCIPLE OF FUZZY DIRECT TORQUE CONTROL

The Fuzzy Logic system involves three steps fuzzification, application of Fuzzy rules and decision making and defuzzification [10]. Fuzzification involves mapping input crisp values to Fuzzy variables. Fuzzy inference consists of Fuzzy rules and decision is made based on these Fuzzy rules. These Fuzzy rules are applied to the fuzzified input values and *Fuzzy* outputs are calculated. In the last step, a defuzzifier converts the Fuzzy outputs back to the crisp values.

The Fuzzy controller in this paper is designed to have three Fuzzy input Variables and one output variable for applying the Fuzzy control to direct torque Control of Induction Motor[8], there are three variable input Fuzzy Logic variables - the stator flux error, electromagnetic torque error, and angle of flux stator.[12]

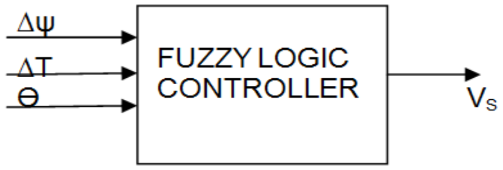

Fig.4. Fuzzy Logic controller

The membership functions of these Fuzzy sets are triangular with two membership function N, P for the flux-error, three membership functions N, Z, P for the torque-error, six membership variables for the stator flux position sector and eight membership functions for the output commanding the inverter[1]. The inference system contains thirty six Fuzzy rules which is framed in order to reduce the torque and flux ripples. Each rule takes three inputs, and produces one output, which is a voltage vector. Each voltage vector corresponds to a switching state of the inverter. The switching state decides the pulse to be applied to the inverter. The Fuzzy inference uses Mamdani's procedure for applying Fuzzy rules which is based on min-max decision.

Depending on the values of flux error, torque error and stator flux position the output voltage vector is chosen based on the Fuzzy rules [1]. Using Fuzzy Logic controller the voltage vector is selected such that the amplitude and flux linkage angle is controlled. Since the torque depends on the flux linkage angle the torque can be controlled and hence the torque error is very much reduced.

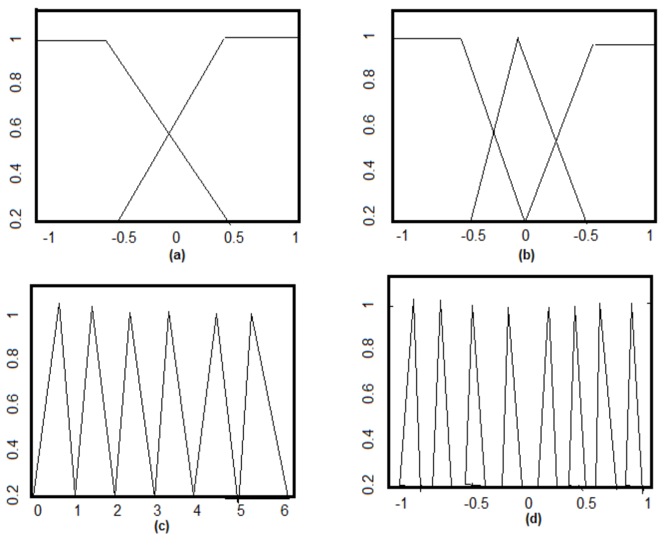

Fig.5. Fuzzy membership functions. (a) flux-error, (b) torque-error, (c) stator flux position sector, (d) pulses controlling the PWM inverter

4. SIMULATION RESULTS AND DISCUSSONS

First the conventional DTC scheme is applied to the induction motor to check the performance under no load and then full load.

A. *Start up with No Load*:

The rotor speed response in Fig.6(a) behaves linearly during start-up. This is validating the equation of the speed for no load running with single inertia and negligible friction as below:

$$wr=\int(Te/J)dt \tag{9}$$

In this no load situation, the rotor speed would eventually accelerate to synchronous speed. The response is shown in Fig.6(a). The locus of the stator fluxes is presented in Fig.6(b) and Fig.7(b). Since the stator flux magnitude is constantly maintained in the hysteresis band, the locus draws the figure of a circle.

B. *Dynamic Behaviour:*

The transient performance of the developed DTC model has been tested by applying a step load torque command from +20 to -20 Nm on the mechanical dynamics. As seen in Fig.6(f) and Fig.7(d) estimated electromagnetic torque shows a good response. This demonstrates that the developed DTC achieved high dynamic performance in response to changes in demand torque. However, there are some performance degradation with torque overshoot in the torque transient owing to the hysteresis controllers used.

Simulation of conventional direct torque control and direct torque control based on Fuzzy Logic are shown and parameters used are as follows.

Power P	7.5 kVA
Voltage V	400V
Number of poles	4
Frequency f	50 Hz
Stator resistance R_s	0.6Ω
Rotor resistance R_r	0.4Ω
Stator inductance L_s	0.123H
Stator inductance L_r	0.1274H
Mutual inductance L_m	0.12H

C. *Conventional DTC:*

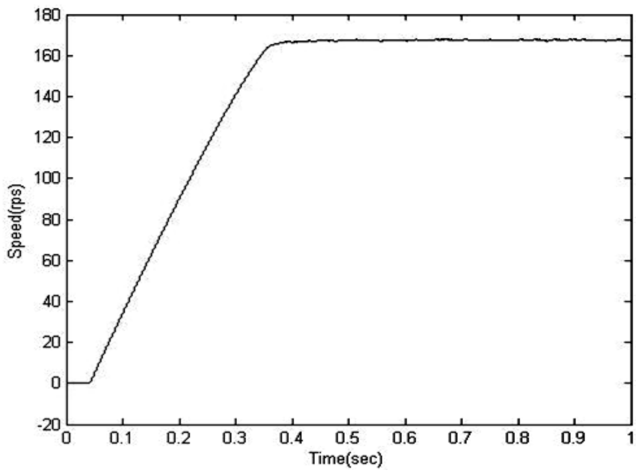

Fig.6(a). Rotor speed

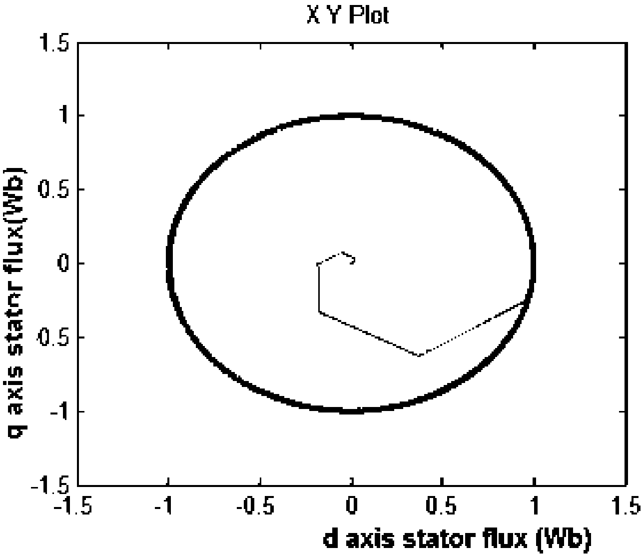

Fig.6(b). Locus of Stator flux

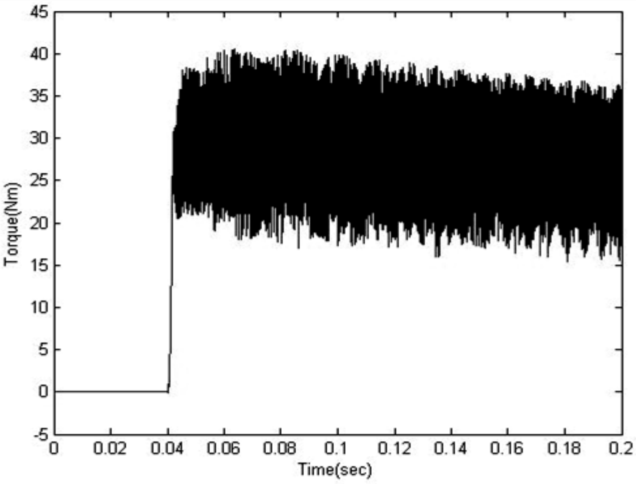

Fig.6(c). Torque

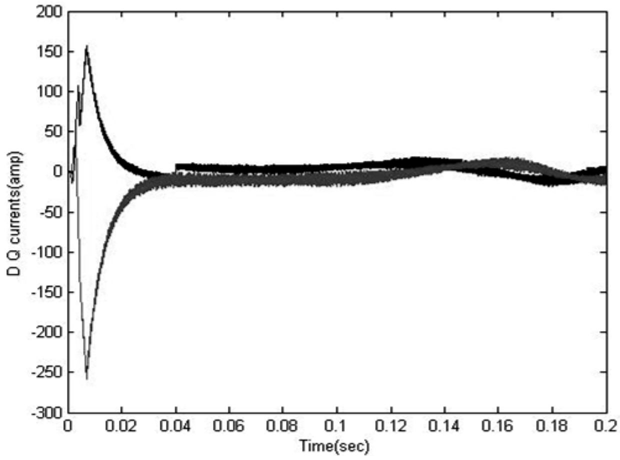

Fig.6(d). D-axis and Q-axis Stator current

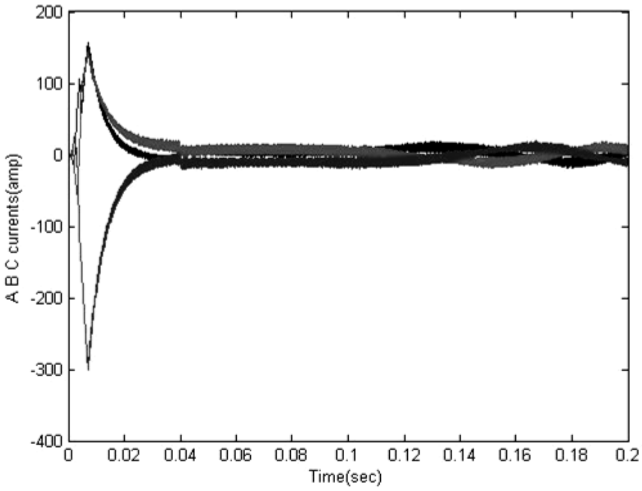

Fig.6(e). Stator current

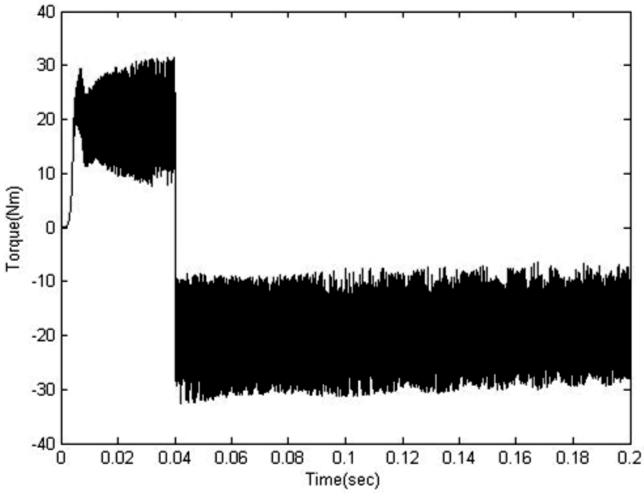

Fig.6(f). Dynamic Torque Response of DTC during Load Step Command from +20 Nm to -20 Nm

D. DTC using Fuzzy Logic:

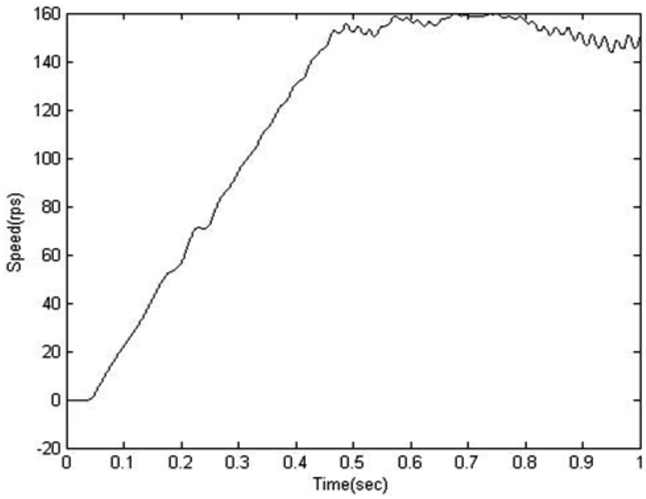

Fig.7(a). Rotor speed

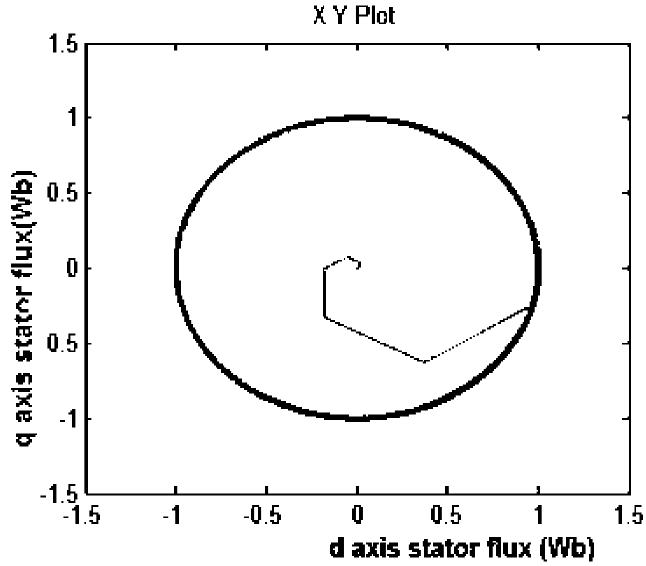

Fig.7(b). Locus of stator flux

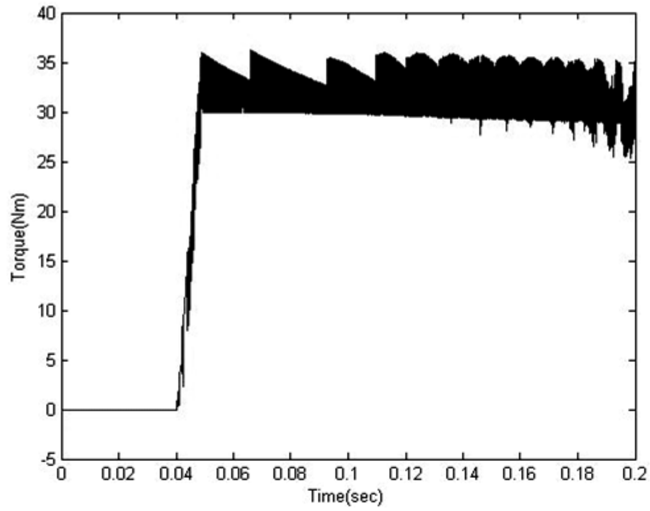

Fig.7(c). Torque

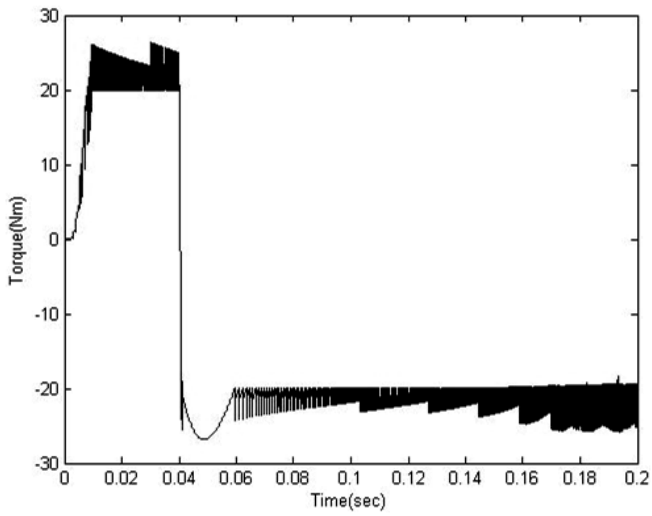

Fig.7(d). Dynamic Torque Response of Fuzzy Logic Based DTC during Load Torque Step Command from +20 Nm to -20 Nm

5. CONCLUSION

The drawback of DTC is high torque and flux ripple and is reduced to a certain extent by means of Fuzzy based DTC .This can be observed from Fig.6(c) and Fig.7(c). Both the methods show a circular flux trajectory. A step load torque of +20 Nm to -20 Nm is applied and torque ripples are also reduced which is noticeable in Fig.6(f) and Fig.7(d). The Fig.6(a) and Fig.7(a) shows the rotor speed for both the methods and the speed is oscillatory in fuzzy based DTC but settles down in a short period of time and it is due to slow transient response to step changes in torque response. In this paper direct torque control was implemented using Fuzzy Logic and the results are compared with conventional DTC. By using Fuzzy Logic based DTC the torque ripples are considerably reduced.

REFERENCES

[1] C.B. Jabeur-Seddik and F. Fnaiech, “Hysteresis and Fuzzy Based Nonlinear Controllers for Direct Torque Control of Induction Machine”, *IEEE International conference on Industrial Technology, ICIT’04*, Vol. 1, pp. 38-43, 2004.

[2] I. Takashashi and T. Noguchi, “A New-Quick Response and High-Efficiency Control Strategy of Induction Motor”, *IEEE Trans. On Industrial Applications*, Vol. 22, No. 5, pp.820-827, 1986.

[3] M. Depenbrock, “Direct self-Control (DSC) of Inverter-Fed Induction Machine”, *IEEE Transactions on Power Electronics*, Vol. 3, No. 4, pp.420-429, 1988.

[4] Y. Xia and W. Oghannna, “Study on Fuzzy Control of Induction Machine with Direct Torque Control Approach”, *Proceedings of IEEE International Symposium on Industrial Electronics*, Vol. 2, pp. 625-630, 1997.

[5] R. Toufouti, S. Meziane and H. Benalla, “Direct Torque Control for Induction Motor Using Fuzzy Logic”, *ACSE Journal*, Vol. 6, No. 2, pp. 19-26, 2006.

[6] Jia-Quing Yang and Jin Huang, “A New Full Speed Range Direct Torque Control Strategy for Induction Machine”, *Proceedings of the International Conference on Machine Learning and Cybernetics,* Vol. 1, pp. 568-573, 2004.

[7] Jia-Qiang Yang and Jin Huang, “Direct Torque Control System for Induction Motors with Fuzzy Speed Pi Regulator”, *Proceedings of the International Conference on Machine Learning and Cybernetics,* Vol. 2, pp. 778-783, 2005.

[8] Hui-Hui Xiao, Shan Li, Pei-lin Wan and ming-Fu Zhao, “Study on Fuzzy Direct torque Control System”, *Proceedings of the Fourth International Conference on Machine Learning and Cybernetics*, Vol. 3, pp. 1537-1540, 2002.

[9] Jagadish H. Pujar and S.F.Kodad, “Direct Fuzzy Control of An AC Drive”, Proceedings of *International Conference on Advances in Computing, Control and Telecommunication Technologies*, pp. 275-277, 2009.

[10] M. Vasudevan and R. Arumugan, “High Performance Adaptive intelligent Direct Torque Control Schemes For

Induction Motor", *Serbian Journal of Electrical Engineering,* Vol. 2, No.1, pp. 93-116, 2005.

[11] Rintu Khanna, Manisha Singla and Gurpeet Kaur "Fuzzy logic based Direct Torque Control of Induction Motor", *IEEE Proceedings of Power and Energy Society General meeting,* pp.1-5, 2009.

[12] Guohan Lin and Zhiewei Xu, "Direct Torque Control of Induction motor based on Fuzzy Logic", *Proceedings of the International Conference on Computer Engineering and Technology,* Vol. 4, pp. 651-654, 2010.