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Minimization of Torque Ripple and Multi Quadrant Operation of Direct Torque Control for Three Phase Induction Motor Using Fuzzy Logic Controller

P.Ramesh Babu[1]**, S. Ramprasath**[2]**, N.Vijayasarathi**[3]
Department of Electrical and Electronics Engineering, Saranathan College of Engineering, Tamilnadu, India[1,2,3]

Abstract: This manuscript deals with multi quadrant operation of Fuzzy Logic Controller based Direct Torque Control (DTC) of three phase Induction Motor drive using MATLAB and its toolbox SIMULINK. The major problem that is usually associated with Direct Torque Controlled drive is presence of ripple in electromagnetic torque. To overcome the problem direct torque control method has been optimized by using fuzzy logic controller. The speed of the motor is estimated through motor model and it's compared with reference speed. The speed error is processed through fuzzy logic controller and the reference torque is obtained. According to the variation of speed, the reference torque is varied. Due to this, the reference torque is maintained within a limit and torque ripple is also reduced. The presented fuzzy based control scheme combines the benefits of fuzzy logic control technique along with direct torque control technique. With aid of the proposed model, the steady-state and dynamic characteristics of current, flux, speed and torque of three phase induction motor in all quadrants can be effectively examined and analyzed.

Keywords: Direct torque control, Induction Motor, Fuzzy logic controller.

I. INTRODUCTION

Recent years, fuzzy logic control has found many applications in industries for drive control. This is so largely increasing because fuzzy logic controller has the capability to control nonlinear systems where no mathematical model is available [1]. AC motors combined with their drives have replaced DC motors in industrial applications due to their lower cost, better reliability, lower weight, and reduced maintenance requirement. Scalar speed control method has good steady state response but poor dynamic response [3]. To achieve good dynamic response as well as good steady state response, vector control was introduced but it has complexity in construction and control [3]. To overcome the disadvantages of field oriented control technique, in the middle of 1980's a new quick response for the torque control of induction motors was proposed by Takahashi as direct torque control (DTC) [5]. DTC provides quick response with simple control structure and hence, this technique is most popularity in industries [5]. Though, DTC has good dynamic performance, it has some drawbacks such as high ripple in torque due to variation in switching frequency of the inverter. To conquer this problem, various techniques have been implemented like space vector modulation techniques [5], variable hysteresis bands [6] and intelligent control methods [10].

Even though all pervious works made a great contribution to control torque ripple by using fuzzy logic control, there is no adequate literature available for four quadrant operation of Fuzzy logic controller based DTC of Induction Motor drive. This paper proposes four quadrant operation of Fuzzy logic control based direct torque control (DTC) to improve dynamic response and decrease the torque ripples. Hence the proposed model can be implemented for electrical vehicle applications where perfect control of torque matters the most and accuracy of speed is not of much importance. Fig.1 shows the block diagram of proposed model.

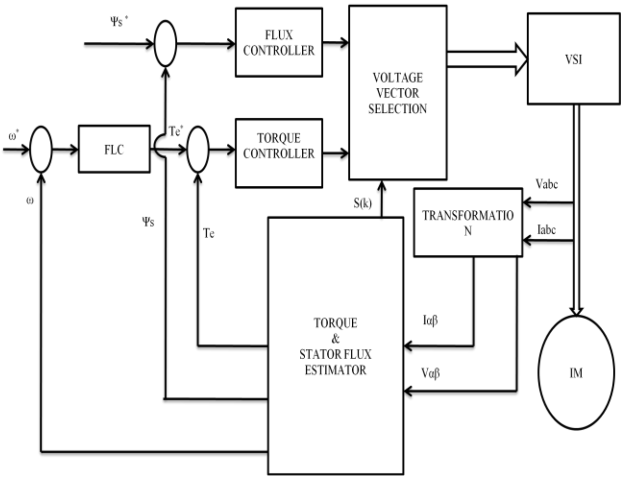

Fig.1 Block Diagram of Proposed Model

II. MODELLING OF INDUCTION MOTOR

The induction motor, which is the most widely used motor type in the industry, has been favored because of its good self-starting capability, simple and rugged structure, low cost and reliability, etc. Along with variable frequency inverters, induction motors are used in many adjustable speed applications. The concept of vector control has opened up a new possibility that induction motors can be controlled to achieve dynamic performance as good as that

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of DC motors [2]. In order to understand and analysis vector control, the dynamic model of the induction motor is necessary.

A. Variables in Arbitrary Reference Frame

The voltage equations of induction motor in arbitrary reference frame [8] given by,

$$V_{qs} = r_s i_{qs} + \omega\lambda_{ds} + \rho\lambda_{qs} \quad (1)$$

$$V_{ds} = r_s i_{ds} - \omega\lambda_{qs} + \rho\lambda_{ds} \quad (2)$$

$$V_{os} = r_s i_{os} + \rho\lambda_{os} \quad (3)$$

$$V_{qr}' = r_r' i_{qr}' + (\omega - \omega_r)\lambda_{dr}' + \rho\lambda_{qr}' \quad (4)$$

$$V_{dr}' = r_r' i_{dr}' - (\omega - \omega_r)\lambda_{qr}' + \rho\lambda_{dr}' \quad (5)$$

$$V_{or}' = r_r' i_{or}' + \rho\lambda_{or}' \quad (6)$$

The Flux linkage equation of three phase induction motor in arbitrary reference frame [8] given by,

$$\lambda_{qs} = L_{ls} i_{qs} + L_m\left(i_{qs} + i_{qr}'\right) \quad (7)$$

$$\lambda_{ds} = L_{ls} i_{ds} + L_m\left(i_{ds} + i_{dr}'\right) \quad (8)$$

$$\lambda_{os} = L_{ls} i_{os} \quad (9)$$

$$\lambda_{qr}' = L_{lr}' i_{qr}' + L_m(i_{qs} + i_{qr}') \quad (10)$$

$$\lambda_{dr}' = L_{lr}' i_{dr}' + L_m(i_{ds} + i_{dr}') \quad (11)$$

$$\lambda_{or}' = L_{lr}' i_{or}' \quad (12)$$

B. Current Equation

By solving flux linkage Equations for currents, we can obtain current equations as,

$$i_{qs} = \frac{1}{X_{ls}}(\psi_{qs} - \psi_{mq}) \quad (13)$$

$$i_{ds} = \frac{1}{X_{ls}}(\psi_{ds} - \psi_{md}) \quad (14)$$

$$i_{os} = \frac{1}{X_{ls}}(\psi_{os}) \quad (15)$$

$$i_{qr}' = \frac{1}{X_{lr}'}(\psi_{qr}' - \psi_{mq}) \quad (16)$$

$$i_{dr}' = \frac{1}{X_{lr}'}(\psi_{dr}' - \psi_{md}) \quad (17)$$

$$i_{or}' = \frac{1}{X_{lr}'}(\psi_{or}') \quad (18)$$

Where,

$$\psi_{mq} = X_M(i_{qs} + i_{qr}') \quad (19)$$

$$\psi_{md} = X_M(i_{ds} + i_{dr}') \quad (20)$$

C. Electromagnetic Torque and Speed Equation

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\frac{\psi_{ds}}{\omega_b} i_{qs} - \frac{\psi_{qs}}{\omega_b} i_{ds}\right) \quad (21)$$

$$\omega_r = \int \frac{(T_e - T_L)}{2} P \; dt \quad (22)$$

D. Simulink Model of Induction Motor

The model of induction motor has been implemented in MATLAB\SIMULINK with the aid of equations (1) to (22). The model has been simulated in arbitrary reference frame by assigning zero to reference frame speed [8].

III. DIRECT TORQUE CONTROL

A. Principle of DTC

Direct torque control was developed by Takahashi and Depenbrock [4] as an alternative to field-oriented control. In a direct torque controlled (DTC) induction motor drive supplied by a voltage source inverter, it is possible to control directly the stator flux linkage ψ_s and the electromagnetic torque by the selection of an optimum inverter voltage vector [2]. The selection of the voltage vector of the voltage source inverter is made to restrict the flux and torque error within their respective flux and torque hysteresis bands and to obtain the fastest torque response and highest efficiency [3] at every instant.

B. Torque Expression of Induction Motor

The electromagnetic torque in the three phase induction machines [2] can be expressed as follows,

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\overline{\psi_s} \times \overline{I_s} \quad (23)$$

Where ψ_s is the stator flux, I_s is the stator current and P the number of poles. The previous equation can be modified and expressed as,

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\frac{L_m}{L_r L_s'}|\psi_r||\psi_s| sin\gamma \quad (24)$$

γ is the angle between fluxes.

From the above expression, when the rotor flux vector ψ_r is constant and the stator flux vector ψ_s is changed incrementally, the angle between vectors ψ_r and ψ_s, γ is incremented by $\Delta\gamma$. The incremental ΔT_e expression [2] is given by,

$$\Delta T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\frac{L_m}{L_r L_s'}|\psi_r||\psi_s + \Delta\psi_s| sin\Delta\gamma \quad (25)$$

C. Control Strategy of DTC

The reference stator flux $\psi_s{}^*$ and torque $T_e{}^*$ magnitudes are compared with the respective estimated values and the errors are processed through hysteresis-band controller. The flux loop HB controller has 2 levels [2] of output according to the following relations,

$$H_\psi = 1 \;\; for \;\; E_\psi > +HB_\psi \quad (26)$$

$$H_\psi = -1 \;\; for \;\; E_\psi < -HB_\psi \quad (27)$$

The torque loop controller has 3 levels [2] of digital output as per the following relations,

$$H_{Te} = 1 \;\; for \;\; E_{Te} > +HB_{Te} \quad (28)$$

$$H_{Te} = -1 \;\; for \;\; E_{Te} < -HB_{Te} \quad (29)$$

$$H_{Te} = 0 \;\; for \;\; -HB_{Te} < E_{Te} < +HB_{Te} \quad (30)$$

The feedback flux ψ_s and torque T_e are calculated from machine terminal voltages and currents. The signal computation block also calculates the sector number S(k) in which the flux vector ψ_s lies. The voltage vector table receives the input signals H_ψ, H_{Te} and S(k) and generates the appropriate control voltage vector (switching states) for the inverter using a lookup table [2], which is shown in Table.1.

TABLE I: Lookup Table for DTC

H_ψ	H_{Te}	$S(1)$	$S(2)$	$S(3)$	$S(4)$	$S(5)$	$S(6)$
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_6	V_1	V_2	V_3	V_4	V_5
-1	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_7	V_0	V_7	V_0	V_7	V_0
	-1	V_5	V_6	V_1	V_2	V_3	V_4

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D. DTC Simulink Model

The complete model of DTC using SIMULINK/MATLAB is shown in Fig.2.

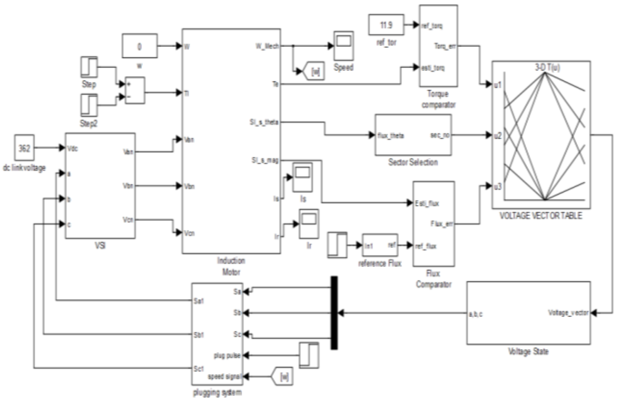

Fig.2. DTC Simulink Model

IV. FUZZY BASED DIRECT TORQUE CONTROL

A. Fuzzy Logic speed Regulator Model

The overall model for fuzzy logic based speed control system for direct torque control induction motor drive is shown in Fig.3. In the Fuzzy based DTC scheme of voltage source inverter-fed induction motor drive system, simultaneous control of the torque and the flux linkage was required. So, the reference torque to DTC is fed from speed loop of the IM drive as shown in Fig.3 which is regulated using FLC. The input linguistic variables speed error (E), change in speed error (CE) and output linguistic variable Torque reference.

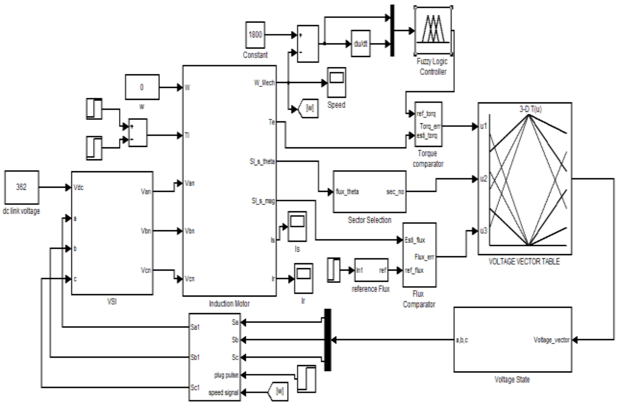

Fig.3. Fuzzy based DTC Simulink Model

B. Fuzzification

In this stage, the input variables for the fuzzy control speed regulator are speed error (E) and derivative of speed error (CE) are converted in to fuzzy variables. The triangular and trapezoidal shape membership functions are chosen for the control variables. Speed error and change in speed error variables are divided into seven overlapping fuzzy sets NL (Negative Large), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (positive Medium) and PL (Positive Large). The division of seven error and change in error fuzzy set is shown in Fig.4 & Fig.5 respectively. The output variable is reference torque which is divided into nine overlapping fuzzy set NVL (Negative Very Large), NL (Negative Large), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (positive Medium), PL (Positive Large) and PVL (Positive Very Large). The division of nine output torque is shown in Fig.6.

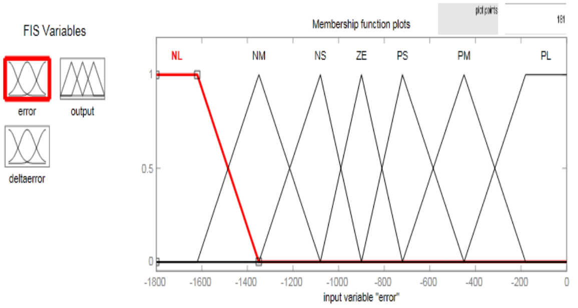

Fig.4. Membership function for speed error

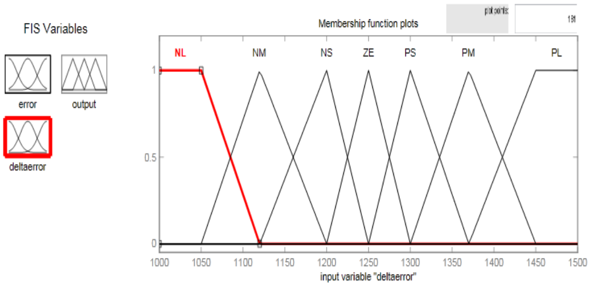

Fig.5. Membership function for change in speed error

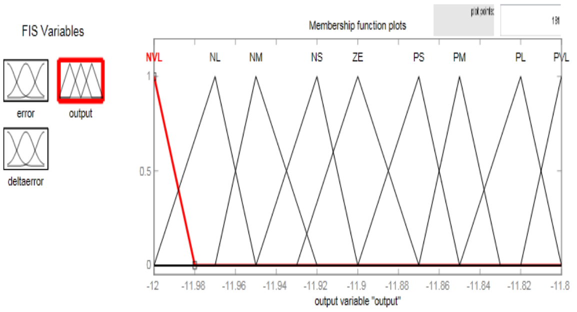

Fig.6. Membership function for output

C. Knowledgebase and Interferance Stage

Knowledge base involves defining the rules represented as IF-THEN [6] statements governing the relationship between input and output variables in terms of membership functions. In this stage, the variables *Error (E)* and *Change in error (CE)* are processed by an inference engine that executes 49 rules (7x7) as shown in Table 2.

TABLE II: Fuzzy Control Rules

CE E	NL	NM	NS	ZE	PS	PM	PL
NL	NVL	NVL	NVL	NL	NM	NS	ZE
NM	NVL	NVL	NL	NM	NS	ZE	PS
NS	NVL	NL	NM	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PM	PL	PVL
PM	NS	ZE	PS	PM	PL	PVL	PVL
PL	ZE	PS	PM	PL	PVL	PVL	PVL

D. Defuzzication

The most used defuzzification method is that of the centre of attraction [6] of balanced heights. Choice is based on the latter owing to the fact that it is easy to implement and does not require much calculation.

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V. SIMULATION RESULTS

Machine Parameters

3 hp, 60Hz, 4 pole, 220 V, 5.8 A, r_s=0.435Ω, r_r'=0.816 Ω, X_{ls}=0.754 Ω, X_m=26.13 Ω, X_{lr}'=0.754 Ω, J=0.089 Kg.m^2,TL=11.9 Nm

The simulation results of DTC and fuzzy based DTC schemes are shown in figures for all four quadrants of operation. The results of DTC based forward motoring (quadrant I) are illustrated in Fig.7 The motor is made to run on reference torque of 11.9 Nm and hence runs in the forward direction. The Torque and speed waveform shown in Fig.8 shows presents of ripples in torque, which have been successfully eliminated using fuzzy based DTC and the torque and speed waveform shown in Fig.9. Fig.10 shows the Comparison of torque for DTC and Fuzzy based DTC.

The results of reverse motoring (quadrant III) are illustrated in Fig.11. The motor is made to run on reference torque of -11.9 Nm and hence runs in the reverse direction. The ripples in torque reduced considerably that is shown in comparison Fig.14. The results of plugging (quadrant II) are illustrated in Fig.15. The motor is allowed to run in the forward direction until 0.6 sec. At t = 0.6 sec, two phases of the induction motor are interchanged to cause the reversal of rmf which in turn causes a quash torque that stops the motor instantly. The motor comes to rest.

The results of regenerative braking (quadrant IV) are illustrated in Fig.17. The motor is allowed to run in load free and the motor reaches the steady state speed of near 1800 rpm. The frequency of the supply is halved at t = 2sec. The synchronous suddenly drops to 900 rpm, this causes a regenerative braking and tends to slow down the motor to the new synchronous speed. The change in speed and torque is shown in Fig.18. The response of the DTC controlled induction motor drive under regenerative braking is shown in Fig.17. Flux plot in Fig.17 shows the change in flux as the frequency is changed. The current and torque deviations during regeneration braking is too large and proper protection circuits are compulsory for the safe operation of the motor.

A. Forward Motoring (Quadrant I)

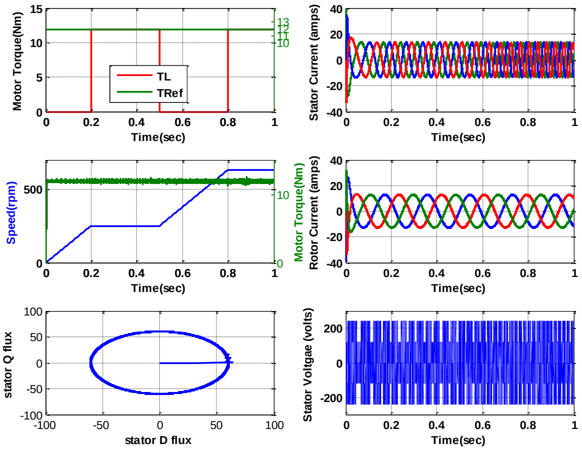

Fig.7. Torque, Speed, Flux, Voltage and Current characteristics of DTC-Forward Motoring

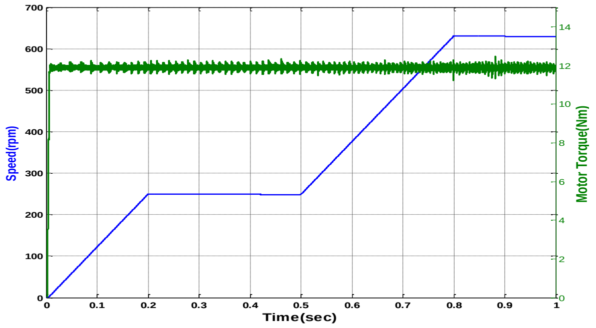

Fig.8. Torque and speed characteristics of DTC-Forward Motoring

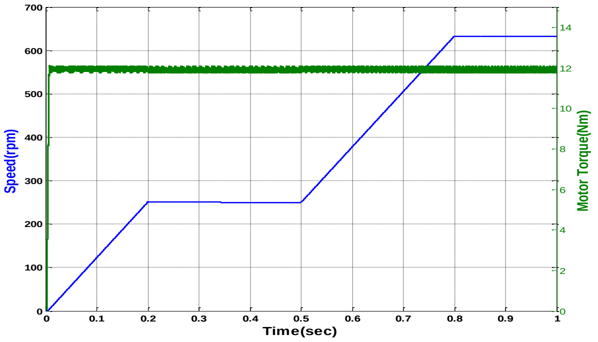

Fig.9. Torque and speed characteristics of Fuzzy based DTC-Forward Motoring

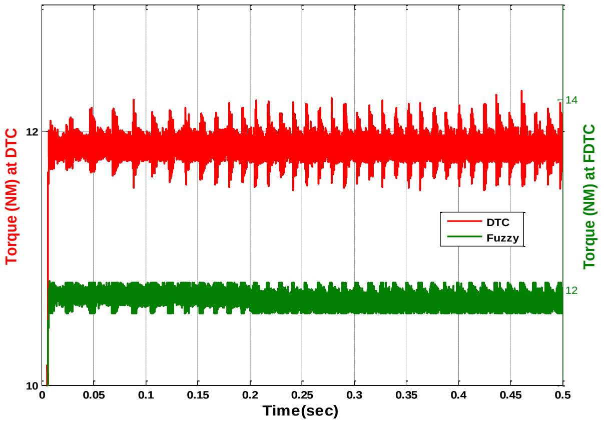

Fig.10. Comparison of Torque Response DTC and Fuzzy based DTC-Forward Motoring

B. Reverse Motoring (Quadrant III)

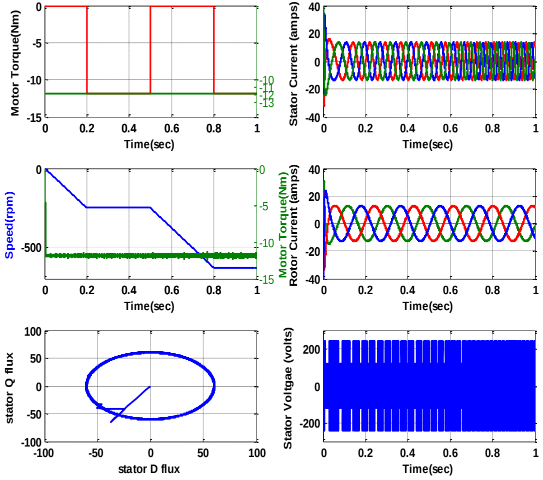

Fig.11. Torque, Speed, Flux, Voltage and Current characteristics of DTC-Reverse Motoring

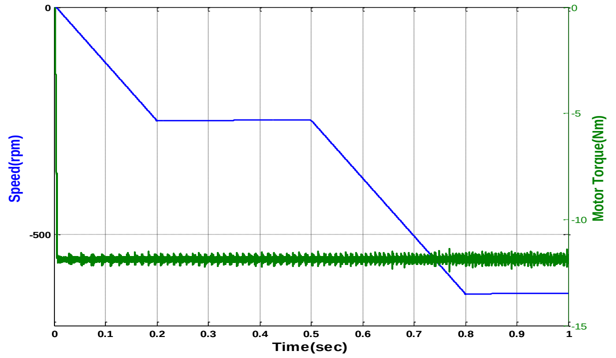

Fig.12. Torque and speed characteristics of DTC-Reverse Motoring

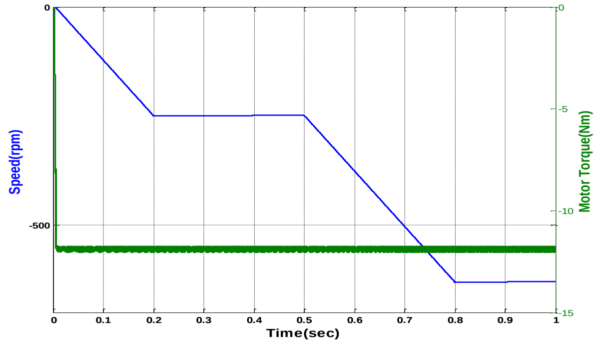

Fig.13. Torque and speed characteristics of Fuzzy based DTC-Reverse Motoring

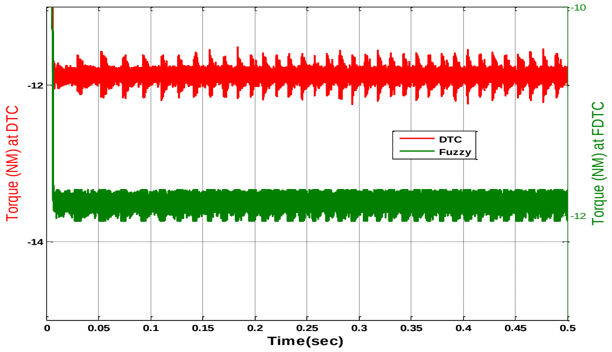

Fig.14. Comparison of Torque Response DTC and Fuzzy based DTC-Reverse Motoring

C. Plugging (Quadrant II)

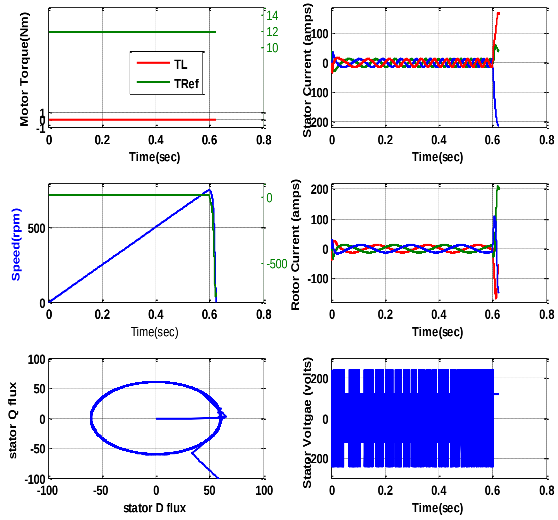

Fig.15. Torque, Speed, Flux, Voltage and Current characteristics of DTC-Plugging

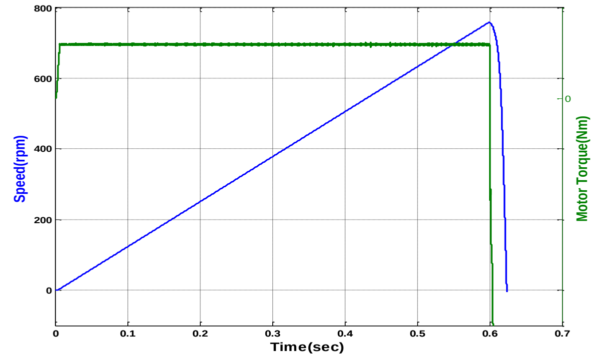

Fig.16. Torque and speed characteristics of DTC-Plugging

D. Regenerative Braking (Quadrant IV)

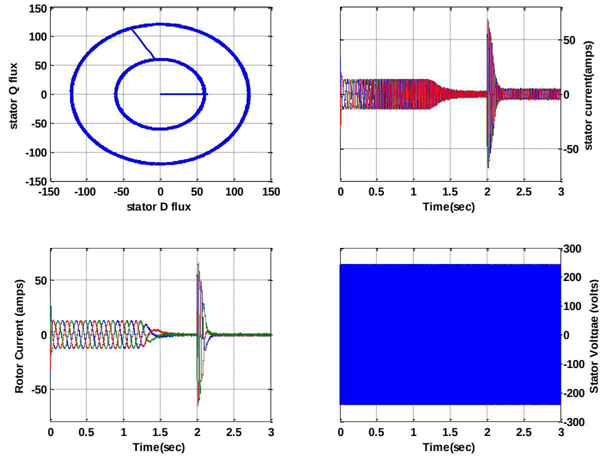

Fig.17. Flux, Voltage and Current characteristics of DTC-Regenerative Braking

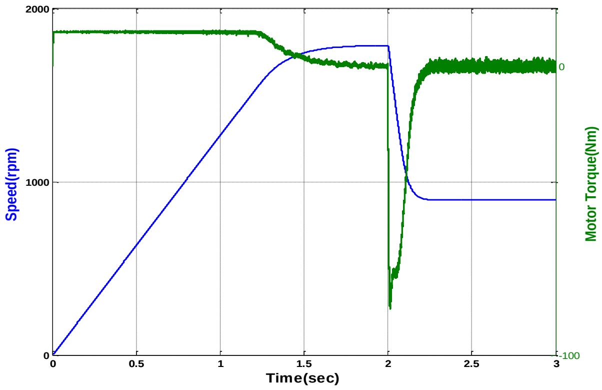

Fig.18. Torque and speed characteristics of DTC-Regenerative Braking

VI. CONCLUSION

In this manuscript Multi Quadrant Operation of Fuzzy based DTC of Three Phase IM Drive in SIMULINK model has been presented. The simulation results show that combining Fuzzy Logic Controller with DTC Technique drastically reduces the Torque Ripple in Forward motoring and Reverse motoring (Reduction of torque ripple is not consider during braking operation because which has minimum transient period). The simulation results also show that the performance of Fuzzy based DTC is better in all the quadrants than DTC. Further the model can be implemented using ANN for better tuning of dynamic performance and torque ripple.

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The proposed model can be expected as an unproblematic design tool for the development of three phase induction motor drives.

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