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Modeling and Performance Analysis of Fuzzy Logic Controller Based Direct Torque Control of VLSI Fed Three

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ABSTRACT—This manuscript deals with fuzzy logic controller based Direct Torque Control (DTC) of three phase Induction Motor Drive using MATLAB and its toolbox SIMULINK. The Direct Torque Control of VSI fed Induction Motor is implemented with the help of Hysteresis Band (HB) controllers (one for flux control and other for torque control), a voltage source inverter and a switching table. The major problem that is usually associated with DTC drive is torque ripple. To overcome the problem direct torque control method has been optimized by using fuzzy logic controller. The presented fuzzy based control scheme combines the benefits of fuzzy logic control technique along with direct torque control technique. With aid of the developed model, the steady and transient-state characteristics of current, speed and torque of three phase induction motor can be effectively examined and analyzed.

KEYWORDS—Direct torque control, induction motor, Fuzzy logic controller, MATLAB/Simulink

I. INTRODUCTION

Fuzzy logic is recently used in drive control applications. 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. Mechanical energy is more than often required at variable speeds, where the speed control system is not a trivial matter. Scalar speed control method has good steady state response but poor dynamic response. To achieve good dynamic response as well as good steady state response, vector control was introduced. But it has complexity in construction and control. In recent years several studies have been carried out for the purpose to find out alternative solution of field oriented control drive to achieve accurate and fast response of flux and torque and also to reduce the complexity of the control system of the drive. 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) [7]. DTC provides quick response with simple control structure and hence, this technique is most popularity in industries [7]. 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. DTC was first introduced, with variations to its original structure to overcome the inherent disadvantages in any hysteresis-based controller, such as high torque ripple [8]. To overcome this problem, various techniques have been implemented like variable hysteresis bands [9], space vector modulation techniques [4] and intelligent control methods [13]. This paper proposes Fuzzy logic control of direct torque control (DTC) to improve dynamic response performance and decrease the torque ripples. Fig 1 shows the block diagram of proposed model.

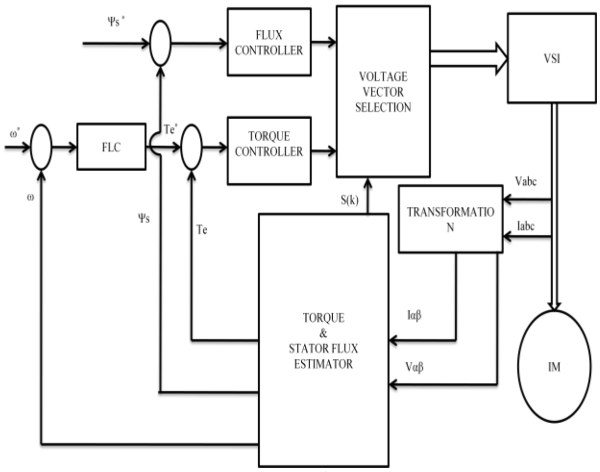

Fig.1 Block Diagram of Proposed Model

II. MODEL OF THREE PHASE INVERTER

A. Voltage Source Inverter

The most common voltage source inverter used in DTC control is the six step inverter. A six step inverter provides the variable frequency AC voltage input to the induction motor in DTC method. The DC supply to the inverter is provided either by a DC source or rectifier.Each leg of the inverter has two switches one connected to high side (+ve) of the DC and the other to low side (-ve); only one of the two can be on at any instant. When the high side gate signal is on the phase is assigned to be1, and assigned 0 when the low side gate signal is on. Considering the combinations of status of phases a, b and c the inverter has eight switching modes (V_a, V_b, V_c = 000-111) two are zero voltage vectors V0 (000) and V7 (111) where the motor terminals is short circuited and the others are nonzero voltage vectors V1 to V6.

B. Inverter Model

Using the switching states of a, b, c the phase voltages connected to the motor winding can be represented as shown in Equation (1), (2) & (3),

$$Van = \frac{Vdc}{3}(2a - b - c) \qquad (1)$$

$$Vbn = \frac{Vdc}{3}(-a + 2b - c) \qquad (2)$$

$$Vcn = \frac{Vdc}{3}(-a - b + 2c) \qquad (3)$$

The inverter block in MATLAB is created using the Equations (1), (2) & (3).

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

A. Induction Motor Modelling

A proper model for the three phase induction motor is essential to simulate and study the complete drive system. The model of induction motor is derived in arbitrary reference frame by making reference speed as zero.

B. Variables in Arbitrary Reference Frame

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

$$V_{qs} = r_s i_{qs} + \omega\lambda_{ds} + \rho\lambda_{qs} \qquad (4)$$

$$V_{ds} = r_s i_{ds} - \omega\lambda_{qs} + \rho\lambda_{ds} (5)$$

$$V_{os} = r_s i_{os} + \rho\lambda_{os} (6)$$

$$V'_{qr} = r'_r i'_{qr} + (\omega - \omega_r)\lambda'_{dr} + \rho\lambda'_{qr} (7)$$

$$V'_{dr} = r'_r i'_{dr} - (\omega - \omega_r)\lambda'_{qr} + \rho\lambda'_{dr} (8)$$

$$V'_{or} = r'_r i'_{or} + \rho\lambda'_{or} (9)$$

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

$$\lambda_{qs}=L_{ls} i_{qs} + L_m\left(i_{qs} + i'_{qr}\right) \qquad (10)$$

$$\lambda_{ds}=L_{ls} i_{ds} + L_m\left(i_{ds} + i'_{dr}\right)(11)$$

$$\lambda_{os}=L_{ls} i_{os} \qquad (12)$$

$$\lambda'_{qr} = L'_{lr} i'_{qr} + L_m(i_{qs} + i'_{qr}) \qquad (13)$$

$$\lambda'_{dr} = L'_{lr} i'_{dr} + L_m(i_{ds} + i'_{dr}) \qquad (14)$$

$$\lambda'_{or} = L'_{lr} i'_{or} \qquad (15)$$

C. Current Equation

By solving flux linkage Equations (10) – (15) for currents, we can obtain current equations as,

$$i_{qs} = \frac{1}{X_{ls}}(\psi_{qs} - \psi_{mq}) \qquad (16)$$

$$i_{ds} = \frac{1}{X_{ls}}(\psi_{ds} - \psi_{md}) \qquad (17)$$

$$i_{os} = \frac{1}{X_{ls}}(\psi_{os}) \qquad (18)$$

$$i'_{qr} = \frac{1}{X'_{lr}}(\psi'_{qr} - \psi_{mq}) \qquad (19)$$

$$i'_{dr} = \frac{1}{X'_{lr}}(\psi'_{dr} - \psi_{md}) \qquad (20)$$

$$i'_{or} = \frac{1}{X'_{lr}}(\psi'_{or}) \qquad (21)$$

Where,

$$\psi_{mq} = X_M(i_{qs} + i'_{qr}) \qquad (22)$$

$$\psi_{md} = X_M(i_{ds} + i'_{dr}) \qquad (23)$$

D. Electromagnetic Torque and Speed Equation

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\frac{\psi_{ds}}{\omega_b} i_{qs} - \frac{\psi_{qs}}{\omega_b} i_{ds}\right) \qquad (24)$$

$$\omega_r = \int \frac{(T_e - T_L)}{2} P\, dt \qquad (25)$$

E. Simulink Model of Induction Motor

The model of induction motor has been implemented in MATLAB\SIMULINK with aid of equation (4) to (25). The model has been simulated in arbitrary reference frame by assigning zero to reference frame speed. Fig.2 shows the overall subsystem of induction motor modeling.

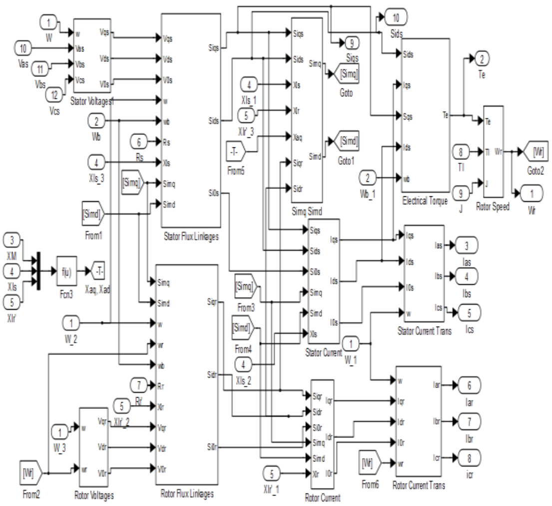

Fig.2 Subsystem of induction motor model

IV. DIRECT TORQUE CONTROL

A. Principle of DTC

Direct torque control was developed by Takahashi and Depenbrock 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. 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 at every instant.

B. Torque Expression of Induction Motor

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

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\overline{\psi_s} \times \overline{I_s} \tag{26}$$

Where $\psi_s$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,

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\frac{L_m}{L_r L_s'}|\psi_r||\psi_s|sin\gamma \tag{27}$$

$\gamma$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 andψ_s, γ is incremented by $\Delta\gamma$. The incremental ΔT_e expression is given by,

$$\Delta T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\frac{L_m}{L_r L_s'}|\psi_r||\psi_s + \Delta\psi_s|sin\Delta\gamma \tag{28}$$

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 of output according to the following relations,

$$H_\psi = 1 \;\; for E_\psi > +HB_\psi \tag{29}$$

$$H_\psi = -1 \;\; for E_\psi < -HB_\psi \tag{30}$$

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

$$H_{Te} = 1 \;\; for E_{Te} > +HB_{Te} \tag{31}$$

$$H_{Te} = -1 \;\; for E_{Te} < -HB_{Te} \tag{32}$$

$$H_{Te} = 0 \;\; for -HB_{Te} < E_{Te} < +HB_{Te} \tag{33}$$

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, which is shown inTable I.

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

D. DTC Simulink Model

The complete model of DTC using SIMULINK is shown in Fig.3.

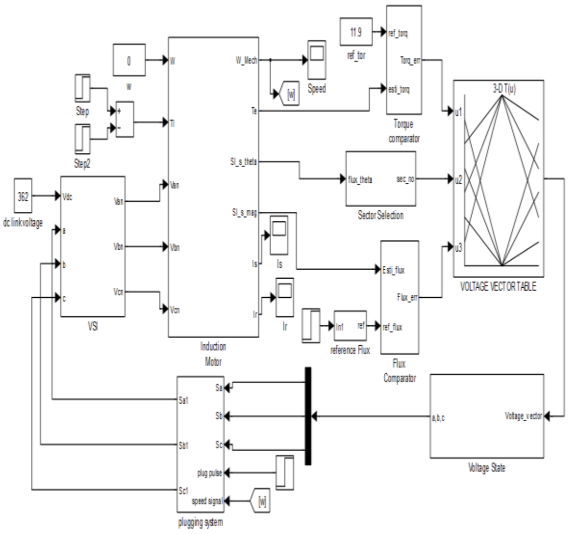

Fig.3. DTC Simulink Model

V. FUZZY BASED DIRECT TORQUE CONTROL

A. *Fuzzy Logic Controller*

One of the reasons for the popularity of Fuzzy Logic Controllers is its logical resemblance to a human operator. It operates on the foundations of a knowledge base which in turn rely upon the various if then rules, similar to a human operator. Unlike other control strategies, this is simpler as there is no complex mathematical knowledge required. The FLC requires only a qualitative knowledge of the system thereby making the controller not only easy to use, but also easy to design.

B. *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.4. 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.5 which is regulated using FLC. The input linguistic variables speed error (E), change in speed error (CE) and output linguistic variable Torque reference.

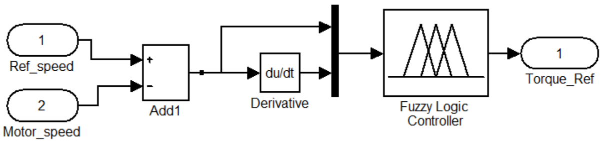

Fig.4. Fuzzy Speed Regulator

C. *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.5& Fig.6 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.7.

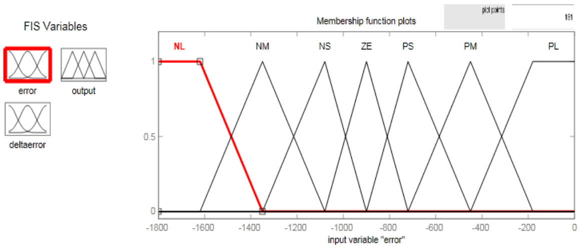

Fig.5. Membership function for speed error

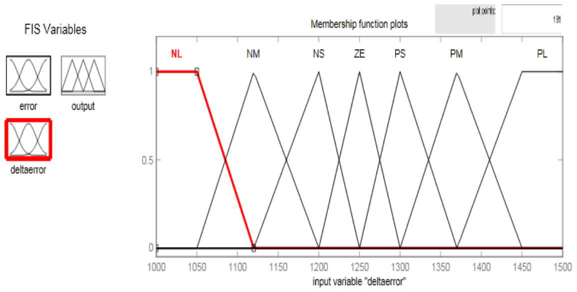

Fig.6. Membership function for change in speed error

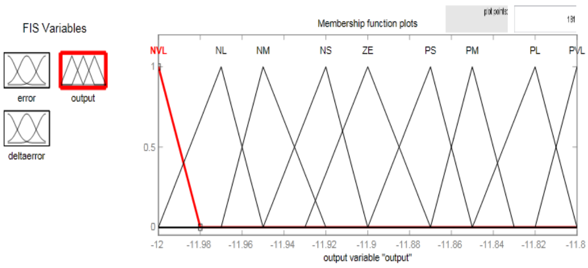

Fig.7. Membership function for output

D. *Knowledgebase and Interferance Stage*

Knowledge base involves defining the rules represented as IF-THEN 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 II.

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

E. Defuzzication

The most used defuzzification method is that of the centre of attraction 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.

VI. SIMULATION RESULTS

A. Output Characteristics of Induction Motor Model

The Induction motor model is run under no-load condition. The motor speed and torque under no-load are plotted in Fig.8, Fig.9 shows the stator flux of IM, The stator and rotor current under no-load condition are plotted in Fig.10 and Fig.11.

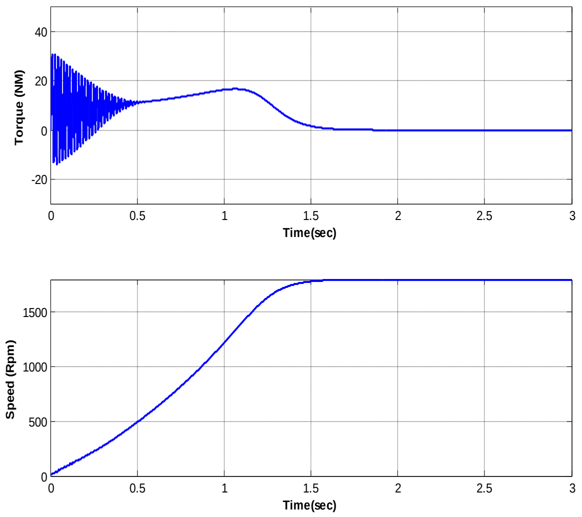

Fig.8. Torque and Speed Curve of IM at No Load

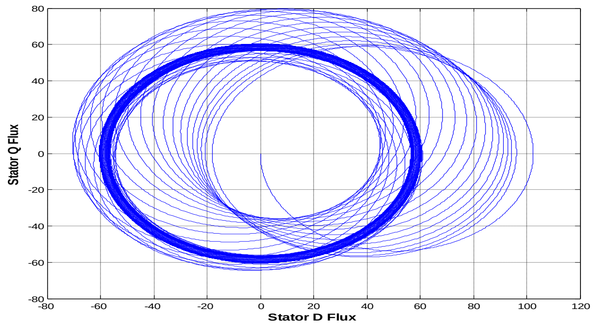

Fig.9. Stator flux of IM

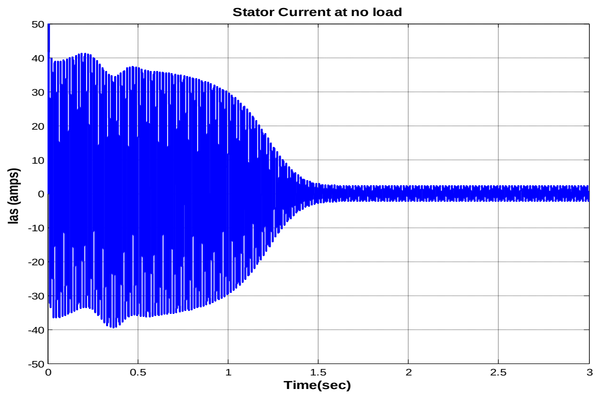

Fig.10. Stator Current of IM at No Load

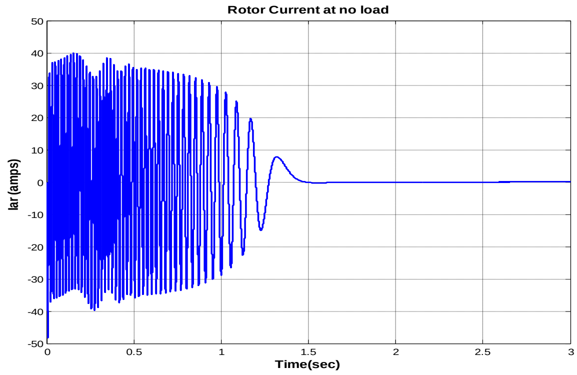

Fig.11. Rotor Current of IM at No Load

B. Output Characteristics of DTC

Fig.12shows the Torque and speed response of DTC, Fig.13 shows theStator Flux locus of IM using DTC. Stator voltage, Current and Rotor Current obtained using DTC is shown in Fig.14. Fig.12shows the Torque response with some ripples. Fig.14 shows the Stator Current and Rotor current taken by motor which is a sinusoidal in nature. The IM takes high current initially and then it becomes a sinusoidal.

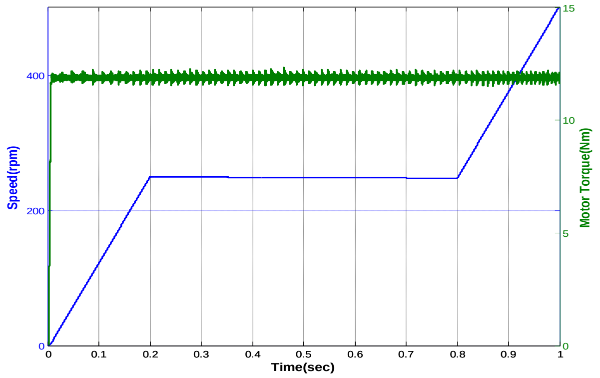

Fig.12. Torque and Speed waveform of DTC based IM

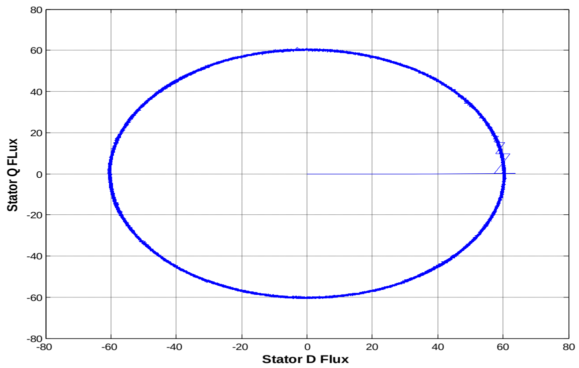

Fig.13. Stator flux locus using DTC

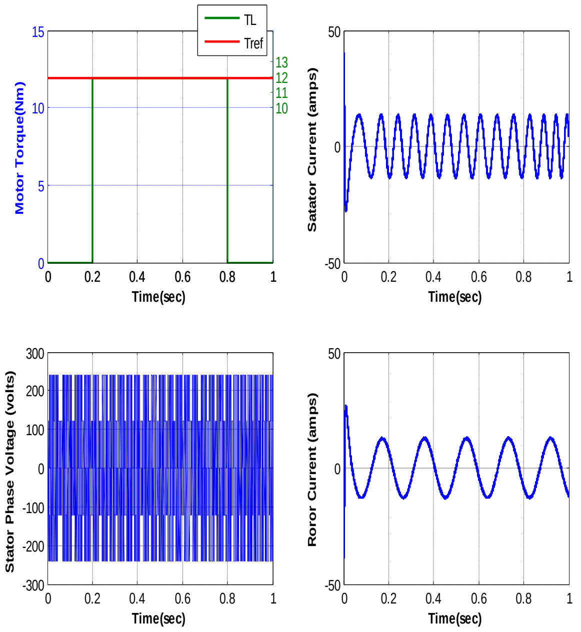

Fig.14. Stator Voltage, Current and Rotor Current Waveform of DTC

C. *Output Characteristics of FDTC*

Fig.15 shows the Torque and speed response of fuzzy based Fuzzy based DTC.

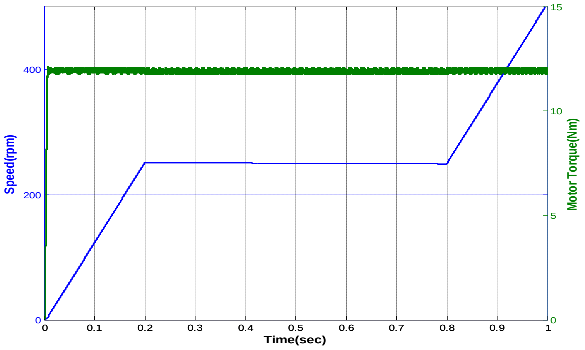

Fig.15. Torque Response of Fuzzy based DTC

D. *Torque Response of DTC and Fuzzy based DTC*

Fig.16 shows the comparison between Torque response of DTC and Fuzzy based DTC.

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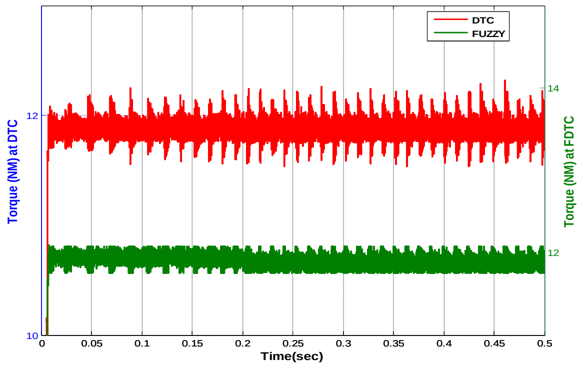

Fig.16. Torque Response of DTC and Fuzzy based DTC

VII. CONCLUSION

The direct torque control of induction motor with fuzzy logic controller is presented in this paper. From the Torque Response Simulink waveform of DTC and Fuzzy based DTC, it has been observed that the torque ripple in Fuzzy based DTC is smoother and the ripples are significantly reduced than that of DTC. Simulations verify the effectiveness of the proposed scheme.

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