Direct Torque and Flux control of Induction Machine using Fuzzy Logic controller

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Abstract: *In this paper improvements in dynamic and steady state performance of direct torque and flux control (DTFC) of induction machine using modified switching table and fuzzy logic controller (FLC) is presented. The major concern in DTFC is selection of the switching state vector in order to meet torque and flux demand of the drive. Main drawbacks of of conventional DTFC is high flux and torque ripples under steady state and variable switching frequency due to hysteresis controllers. Conventional switching table cannot produce accurate voltage vector. Using Fuzzy logic controller (FLC) the torque error, flux error and stator flux angle are divided into smaller subsections. FLC replaces hysteresis controllers and conventional switching table with 180 rule base developed selects optimal switching state, there by reduction in torque and flux ripples and improved dynamic and steady state response is obtained. The proposed methods are evaluated using simulation by MATLAB/Simulink.*

Key words: Artificial Intelligence (AI), Direct Torque and Flux Control (DTFC), Induction Machine (IM), Fuzzy logic Controller (FLC), Voltage source Inverter (VSI).

1. Introduction.

Direct Torque and Flux Control (DTFC) is widely used for quick response and high efficiency control of induction motor drives [1-3]. In DTFC both stator flux and torque are controlled independently from stator side by selection of appropriate inverter switching state from a predefined switching table [4-6]. However conventional DTFC suffer from disadvantages like high torque and stator flux ripples due to hysteresis bands especially at low speed and variable switching frequency. The drive exhibit sluggish speed response for sudden change in reference torque [5-7]. Several techniques have been developed during the past decades to reduce torque and flux ripples [7-11] using multi-level inverters [6-7], by determination of optimized flux based on motor torque [8], by effectively introducing a modulation between an active state and zero switching state using adaptive fuzzy [9]. Another solution to overcome drawback of variable switching frequency by using SVM-DTC in which the hysteresis controllers are replaced by PI controllers [25]. Different strategies adapted for direct torque control: Switching table based DTC with hysteresis bands; hysteresis based direct self-control (DSC) and constant switching DTC-SVM are explained in [26]. The use of deadbeat-direct torque and flux control (DB-DTFC) for highly effective method for induction machine control is presented in [27].It has advantages such as the fastest possible torque dynamics, dynamically loss manipulation capability independent of torque dynamics, and parameter insensitivity[28]. Application of AI techniques like fuzzy logic, neural networks in electrical drives gained great attention in recent years [13-16]. Fuzzy logic controllers are used to select voltage vectors [17], Neural Networks applications for switching state selection [13-15], PI controller replaced by Fuzzy controllers [18-19], and fuzzy logic based duty ratio controllers [5]. The effectiveness of DTFC is in selection of voltage vector based on switching table. Out of AI techniques based on literature, fuzzy logic controller is easier to implement and it can handle the nonlinearity and ambiguity in switching table. Since it is based on expert rule base, it is independent of mathematical model of induction machine and can adapt to nonlinearities and parameters variation. Fuzzy logic controller can easily be implemented using DSP or FPGA using DSPACE [21]. In this paper the conventional DTFC of induction machine with modified switching table is compared with DTFC with Fuzzy logic controller. The Conventional DTFC and DTFC using Fuzzy logic controller are developed in MATLAB/Simulink. Simulation results in validate the reduction in torque and flux ripples and improved dynamic performance of the drive.

2. Induction machine model

The mathematical model of induction motor is developed based on state variable approach referred to stationary reference frame (α, β) using the following equations. The mathematical model of induction machine is given by [20]:

$$\dot{X} = AX + BU; Y = CX \quad (1)$$

$$X = \begin{bmatrix} i_s^{\alpha} \\ i_s^{\beta} \\ \varphi_s^{\alpha} \\ \varphi_a^{\beta} \end{bmatrix} U = \begin{bmatrix} v_s^{\alpha} \\ v_s^{\beta} \end{bmatrix} Y = \begin{bmatrix} i_s^{\alpha} \\ i_s^{\beta} \end{bmatrix} \quad (2)$$

$$L_{ss} = SL_s; S = 1 - \frac{L_m^2}{L_s L_r}; T_r = \frac{L_r}{R_r}; R_a = R_s + R_s \frac{L_m^2}{L_r^2}$$

$$A = \begin{bmatrix} -\frac{R_a}{L_{SS}} & -\omega & \frac{R_r}{L_{SS}L_r} & -\frac{\omega}{L_{SS}} \\ \omega & -\frac{R_a}{L_{SS}} & -\frac{\omega}{L_{SS}} & \frac{R_r}{L_{SS}L_r} \\ -R_S & 0 & 0 & 0 \\ 0 & -R_S & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{L_{ss}} & 0 \\ 0 & \frac{1}{L_{ss}} \\ 1 & 0 \\ 0 & 1 \end{bmatrix} C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (4)$$

R, L, V_s, i_s, ψ_s, ω resistance, inductance, supply voltage, stator current, stator flux and speed of induction motor. The electromagnetic torque developed by IM is given by [22]:

$$T_e = \frac{3}{2} p(\varphi_{s\alpha} i_{s\alpha} - \varphi_{s\beta} i_{s\beta}) \quad (5)$$

$$\dot{\omega} = \frac{1}{J}(T_e - T_L) \quad (6)$$

3. Conventional DTC Using Modified Switching Table.

Fig.1 shows block diagram of conventional DTFC using modified switching table. The motor speed is compared with its reference speed and processed through PI controller of $K_P = 2$ and $K_I = 300$ to produce the reference torque T_e*. The output of PI controller is limited using saturator T_e* = +/- 8 N-m as shown in Fig.2 in order to limit the current drawn by the motor. The torque and stator flux of induction machine is estimated using the following mathematical equations.

$$\varphi_{S(\alpha,\beta)} = \int (v_{S(\alpha,\beta)} - R_S i_{S(\alpha,\beta)}) \quad (7)$$

$$\varphi_S = \sqrt{\varphi_{S\alpha} + \varphi_{S\beta}} \quad (8)$$

$$\theta_S = \tan^{-1}\left(\frac{\varphi_{s\beta}}{\varphi_{s\alpha}}\right) \quad (9)$$

The errors of stator flux magnitude φ_s and electromechanical torque T_e are detected and digitalized by simple two level hysteresis comparators which converts error value into 0 or 1.The stator flux sector is selected based upon the stator flux angle (θ_S) by dividing flux plane into six angular sectors of 60° each as explained in [23].

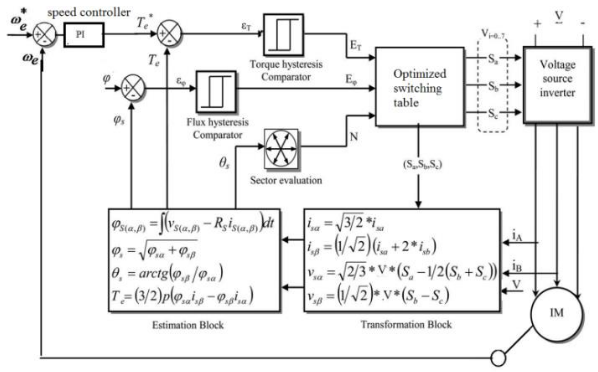

Fig. 1. Block diagram of conventional DTFC with modified switching table

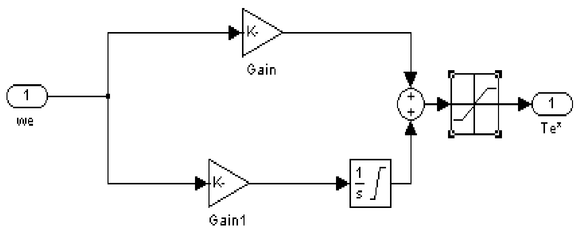

Fig. 2. Block diagram of speed PI controller

Switching sector logic given by Table I selects the optimal switching state of voltage source inverter(VSI). The stator flux magnitude and torque are controlled by selecting one of the available voltage vector based on flux, torque ripple and stator flux angle. The conventional switching table is simplified by replacing three level torque hysteresis comparator of Torque error with two levels. The two hysteresis comparators convert the Torque and Flux error into digital form before applying to modified switching table.

Table 1
Modified switching table

Sector		I	II	III	IV	V	VI
Torque	Flux						
T=0	F=0	V_5	V_6	V_1	V_2	V_3	V_4
	F=1	V_6	V_1	V_2	V_3	V_4	V_5
T=1	F=0	V_3	V_4	V_5	V_6	V_1	V_2
	F=1	V_2	V_3	V_4	V_5	V_6	V_1

In the modified switching table the zero switching states are avoided. Due to addition of hysteresis bands zero useless commutation are avoided when torque and stator flux are very small. The change in the switching state of VSI fed to IM depends upon the present sector and increase or decrease of torque and flux error [17]. When the stator flux is presents in i^{th} sector, the vector V_{i+1} or V_{i-1} is selected to increase the level of the flux, and V_{i+2} or V_{i-2} is selected to decrease it. At the same time, the vector V_{i+1} or V_{i-2} is selected to increase the level of the electromagnetic torque, and V_{i-1} or V_{i-2} is selected to decrease it [17, 21].

3. DTFC using Fuzzy Logic Controller

Using fuzzy logic we can divide the torque error and flux error in to more subsections instead of two states we can have the values between 0 and 1. Other way of dividing the torque and flux errors using multilevel hysteresis bands. The use of multi-hysteresis controller's results in variable switching frequency based on the torque and flux error lies in the particular hysteresis band. Implementation of multilevel hysteresis with classical switching table is not possible, so, we need to modify the switching table for before implementation of CDTC with multi-level hysteresis bands. So using of DTC with FLC is simpler and gives better dynamic performance compared to multi-level hysteresis controllers. The block diagram of DTFC using fuzzy logic controller is shown in Fig.3. The FLC has three inputs stator flux error, electromagnetic torque error and angle of stator flux and one controlled output voltage space vector in order to implement direct torque control of the induction machine [10].

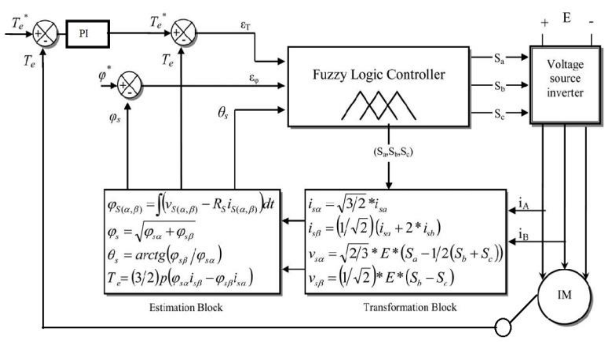

Fig. 3. Block diagram of DTFC with Fuzzy logic controller [21]

FLSC has three inputs flux error(φ_s^*- φ_s), torque error (T_e*- T_e), sector in flux space (θ_s) and one output switching state (n).

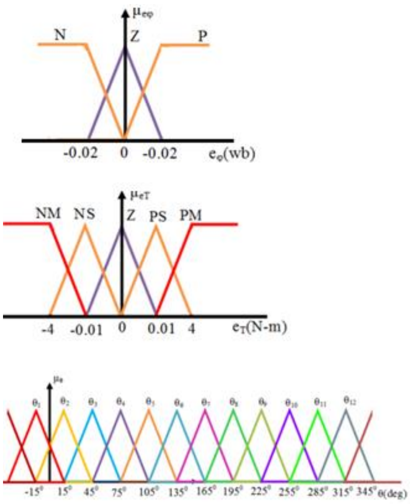

Fig. 4(a), (b) & (c). Membership functions of inputs flux error, torque error and sector

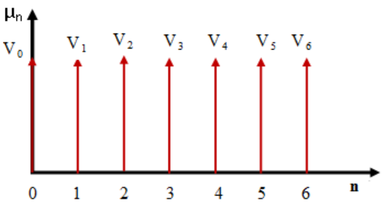

Fig.5. Membership functions of Output of Fuzzy logic switching controller

Table 2 Fuzzy rule base

θ		θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8	θ_9	θ_{10}	θ_{11}	θ_{12}
e_T	e_φ												
PL	P	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1
	Z	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1
	N	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2
PS	P	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1
	Z	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2
	N	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2
ZE	P	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0
	Z	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0
	N	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0
NS	P	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5
	Z	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0
	N	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4
NL	P	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5
	Z	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5
	N	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4

The stator flux error (e_φ) is represented by three linguistic variables: negative (N), zero (Z) and positive (P). The N and P variables are represented by trapezoidal membership functions and Z by triangular membership function as shown in Fig. 4(a). The

Torque error (e_T) is represented by five linguistic variables: Positive Large (PL), Positive Small (PS), Negative Small (NS) and Negative Large (NL) and Z (zero). The NL and PL are represented by trapezoidal membership functions and NS, Z, PS are represented by triangular membership functions as shown in Fig. 4(b).

The Stator flux trajectory is divided in 12 sectors ($\theta_1$to θ_{12}). All fuzzy sets are represented by isosceles triangular membership functions of 60^0 wide and an overlap of 30^0 with neighbourhood fuzzy sets. So that each fuzzy set works for an angle of 30^0.The membership function distribution over 0^0 to 360^0 is shown in Fig. 4(c).

The output of fuzzy controller determines the switching state, represented by output variable n which has seven output states. Out of which one zero switching state and six active switching states as shown in Fig.5 Each state is represented by a sharp triangular membership function: for example n=1 is represented by(0.9,1,1.1).

The mapping of Inputs and output depends upon rule base. The Fuzzy rule is developed based on expert knowledge and intuition in order to meet objective of controller. Since there are three MF's for e_φ, five MF's for e_T and twelve MF' s for θ signals so 3×5×12 = 180 fuzzy rules are developed to select one of seven MF' s for the output as shown in Table 2.

The fuzzy rules are developed using Min-Max method. For example:

Rule: If e_T is PL and e_φ is P and θ is θ_1 then output is V_1.

The minimum of membership functions of e_T , e_φ and θ is selected using Fuzzy AND operation. So output of i^{th} rule depends upon torque error, flux error and stator flux position. The output of FLC is in fuzzified form. The fuzzified output is converted into crisp value using defuzzification process. Out of available methods of defuzzification the 'Centroid' method is employed. The output of the fuzzy controller cannot be directly applied to switches S_A, S_B and S_C. The Boolean expression is developed to convert the output of fuzzy controller before applying to switching sequence of inverter. If output of fuzzy controller is in between 0.5 to 1.5, n = 1 is selected which makes S_A = 1, S_B = 0 and S_C = 0. S_A, S_B and S_C are functions of n, given by

SA (n) is 1 if n = 1 or 2 or 6.
SB (n) is 1 if n = 2 or 3 or 4.
SC (n) is 1 if n = 4 or 5 or 6.

4. Simulation results and Analysis

Fig.6. shows 'Simulink' model of DTC with FLC. As shown in the figure the two hysteresis bands and switching table sector identification block are replaced by Fuzzy controller block. In order to analyse the performance of proposed schemes, simulation models are developed using MATLAB software. In order to test the robustness and dynamic response of the drive, initially induction machine is started at low speed of 50 rad/sec and subjected to step change 100 rad/sec at t=0.4 sec. Initially the induction machine is started on no-load and subjected to a load of 4 N-m at 0.2 seconds and changed to 0 N-m at 0.4 sec. The simulation studies are performed on induction machine with parameters given in Table 3. The simulation carried over a sampling time of 1/10000 sec which is equivalent to sampling frequency of 10 kHz.

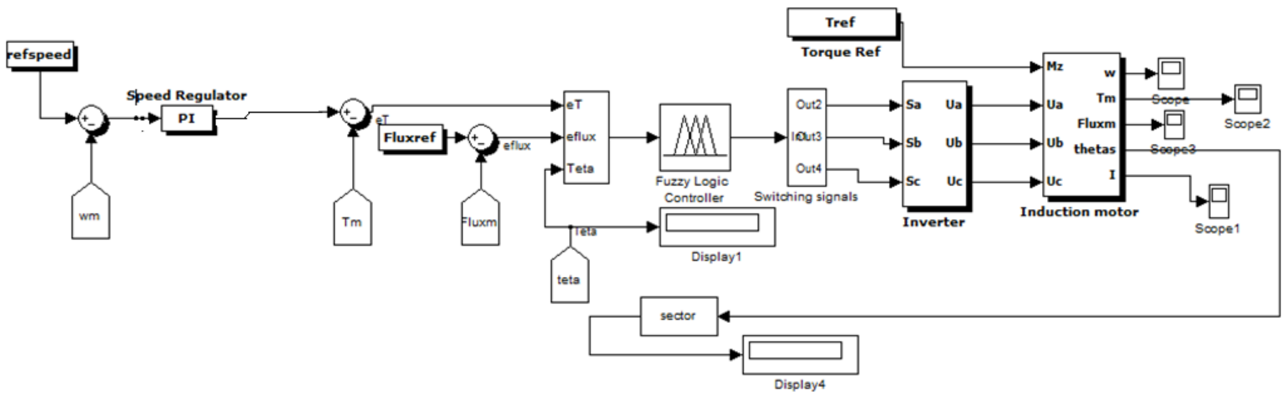

Fig. 6. Simulink model of DTFC with Fuzzy logic controller

Speed response of DTFC of IM using modified switching table and FLC are shown in Fig.7 which illustrates both the schemes able to track reference speed. DTFC with FLC shows reduction in peak overshoot and when subjected to step changes in reference speed.

Table 3
Induction Machine parameters

Symbol	Parameters	Values
P_n	Power	1.1 kW
V_n	Nominal Voltage	400/230 V
I_n	Nominal current	2.6 /4.5 A
N	Motor Speed	1420 rpm
F	Supply frequency	50 Hz
P	Pole pairs	2
R_s	Stator resistance	7.6 Ω
R_r	Rotor resistance	3.6 Ω
L_s	Stator inductance	0.6015 H
L_r	Rotor inductance	0.6015 H
L_m	Mutual inductance	0.5796 H
J	Moment of inertia	0.0049 $Kg \cdot m^2$

Torque response of DTFC of IM using modified switching table and FLC are shown in Fig.8 (a) and 8(b). In DTFC using FLC torque ripples are reduced by 75% compared to conventional DTFC Fig. 8(b) illustrates clear picture of torque ripple reduction. The torque error is 4±2 N-m using conventional DTFC is reduced to 4±0.5N-m in case of DTFC with FLC.

Flux response of DTFC of IM using modified switching table and FLC are shown in Fig.9 (a) and 9(b). Compared to conventional DTFC there is reduction in stator flux ripples using FLC. Fig. 9(b) illustrates clear picture of flux ripple reduction. The torque error is 1±0.6 Wb using conventional DTFC is reduced to 1±0.1 Wb in case of FLC.

Three phase stator current response for both the schemes are shown in Fig. 10(a) and 10(b). DTFC with FLC current contains fewer harmonics compared to conventional DTFC. Fig. 11 shows smooth trajectory path of stator flux during switch of states in DTFC by FLC compared to conventional DTFC, which indicated smooth control of drive and no harmonics during changes in switching state of VSI.

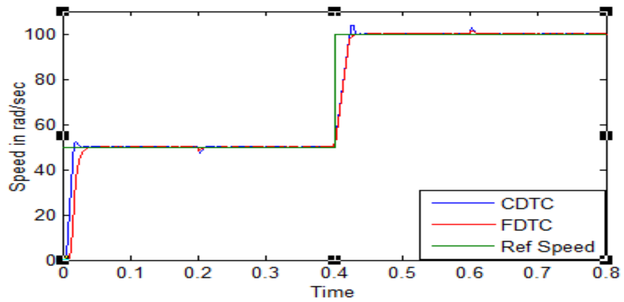

Fig. 7. Motor speed with modified switching table and FLC

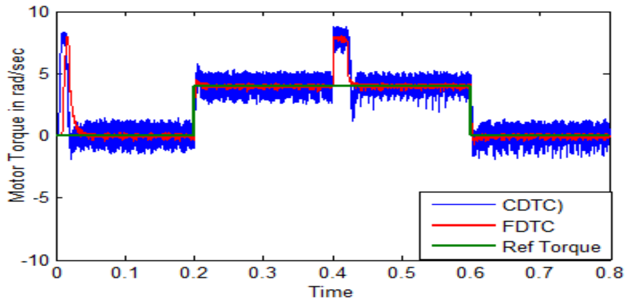

Fig. 8 (a). Motor Torque with modified switching table and FLC

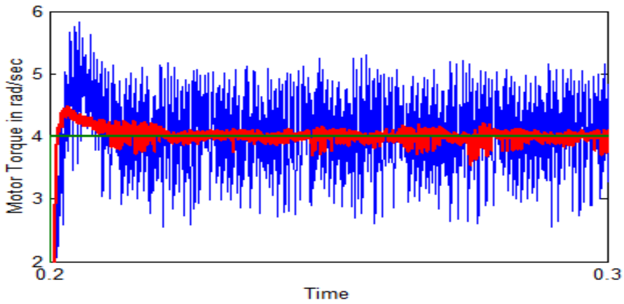

Fig. 8(b). Motor Torque response depicting Reduction in Torque ripples

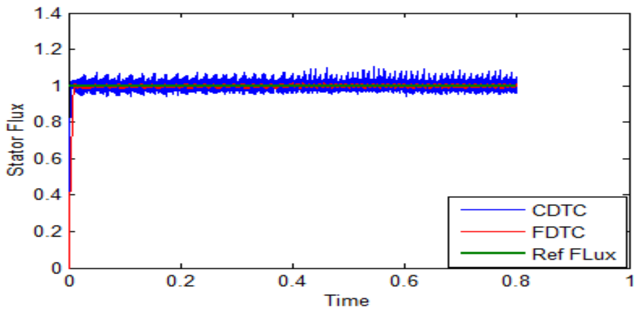

Fig. 9(a). Stator flux response with Conventional switching table and FLC

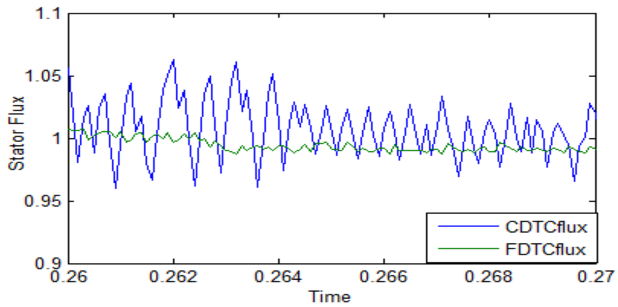

Fig. 9(b). Stator flux response depicting reduction in Flux ripples.

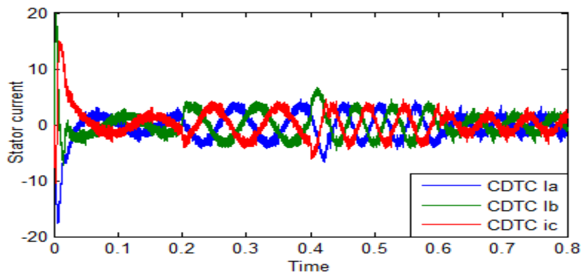

Fig. 10 (a) Stator current with Conventional switching table

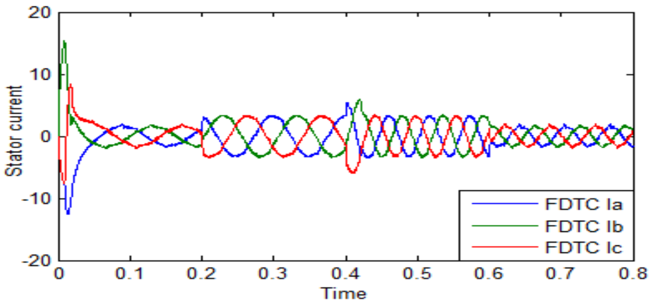

Fig. 10(b). Stator current with and FLC

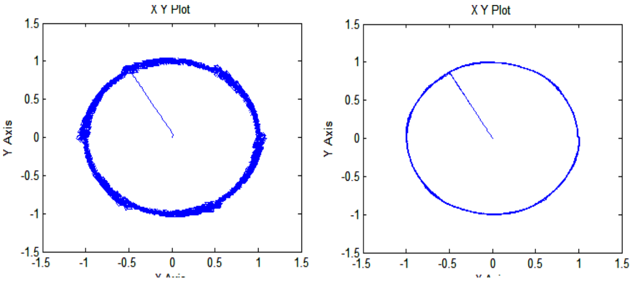

Fig.11. stator flux trajectory path with conventional Switching table and FLC

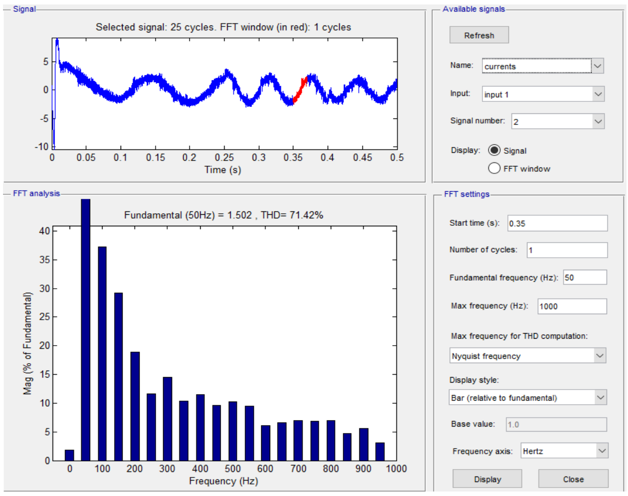

Fig.11. %THD of Stator current

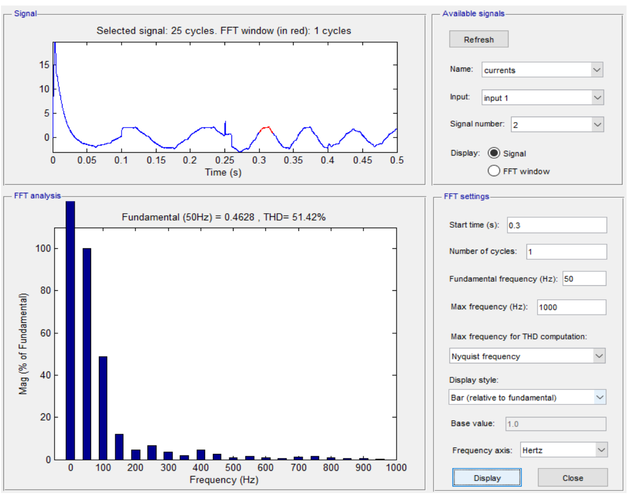

Fig.12. %THD of Stator current

The total harmonic distortion of the stator currents are analysis using Fast Fourier transforms (FFT). Fig.12 shows the THD analysis of stator current in CDTFC is 71.42 %. Fig.13 shows the THD analysis of stator current in DTFC with fuzzy logic switching controller is reduced to 51.42 %. The total harmonics of the stator current drawn by the induction machine in DTFC with FLC are reduced compared to conventional DTFC.

Table 4
Summary of the improvements in DTFC with FLC

Value	Conventional DTFC	DTFC with FLC
Settling time to reach 50 rad/sec in milli seconds	20 ms	25 ms
Torque ripples (N-m)	±2	± 0.5
Flux ripples (Wb)	± 0.6	± 0.1
Current THD in %	71.42	51.42

4. Conclusion

In this paper dynamic and steady state performance of induction machine is improves using DTFC with fuzzy logic controller. Torque and flux ripple in Conventional DTFC of IM are reduced using fuzzy logic controller replacing hysteresis controllers and conventional switching controller compared to conventional DTC. Simulink models of the both schemes are developed in MATLAB/Simulink environment. Out of available software's MATLAB/Simulink is used by present researchers for development of simulation models of electrical drives. Simulation results clearly illustrate reduction in torque and flux ripples and smooth stator flux trajectory path in DTFC with FLC compared to conventional DTFC. The dynamic speed response of drive is improved and harmonics in stator current are reduced. DTFC using FLC exhibit precise control of torque and control compared to Conventional DTFC. The transient and steady state response of motor speed is improved compare to conventional DTFC. The harmonics in stator current are considerably reduced. FLC exhibits precise control of torque and flux compared to conventional switching table.

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