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Direct Torque Control of Induction Motor Using Fuzzy Logic Controller

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Abstract: *The paper presents fuzzy logic based direct torque control (DTC) scheme of an induction motor (IM) and its comparative study using intelligent techniques under varying dynamic conditions are discussed. Direct torque control (DTC) of an induction motor fed by a voltage source inverter is a modest scheme that does not need lengthy computation time and can be implemented without pulse encoders but limitation of this method is having high ripples .These ripples are reduced by using fuzzy logic controller. As the DTC along with IM is mostly nonlinear, fuzzy controller will be more suitable for system. The use of fuzzy logic controller improves the dynamic response of the motor. FLC is designed to select the optimum amplitudes of the three level torque hysteresis controller based on the variation in motor .The modelling and simulation results of FLC based DTC scheme for IM have been confirmed by using software package MATLAB/Simulink.*
Keywords: *Conventional controller, Fuzzy logic controller (FLC, interconnected power system, load frequency control (LFC), PID tuning, tie-line.*

I. Introduction

Among all types of ac machine, the induction machine is most commonly used in industry. These machines are very economical, rugged and reliable and are available in the ranges of fractional horse power (FHP) to multi megawatt capacity.

Basically, there are two types of instantaneous electromagnetic torque controlled AC drives used for high performance applications which are: Vector Control (VC)-Based on stator current control in the field rotating reference using PWM inverter control. Direct Torque Control (DTC)-Based on stator flux control in the stator fixed reference frame using direct control of the inverter switching. Direct torque control (DTC) has become an alternative to well known vector control of IM. This technique was introduced in 1984 by Takahashi and in 1985 by Depenbrock [1].DTC have several advantages over its competitor field oriented control (FOC)[2].The DTC utilizes hysteresis band controllers for both stator flux linkage and motor developed torque controls. Unlike FOC, the DTC scheme does not need any coordinate transformation, pulsewidth modulation (PWM) and current regulators. The PWM stage takes almost ten times longer processing time than the DTC to respond to the actual change [3].The DTC uses flux and torque as primary control variables which are directly obtained from rotor itself. Therefore, there is no need for a separate voltage and frequency controllable PWM. This characteristic makes the DTC simpler and much faster in responding to load changes as compared to the FOC. The major problem in a DTC-based motor drive is the presence of ripples in the motor-developed torque and stator flux. Generally, there are two main techniques to reduce the torque ripples. The first one is to use a multilevel inverter [4] which will provide the more precise control of motor torque and flux. However, the cost and complexity of the controller increase proportionally. The other method is space vector modulation [5]. Its drawback is that the switching frequency still changes continuously

Advantages of intelligent controllers such as fuzzy logic, neural network, neuro-fuzzy, etc., are well known as their designs do not depend on accurate mathematical model of the system and they can handle nonlinearity of arbitrary complexity [6]. Among different intelligent algorithms, fuzzy logic is the simplest, and it does not require intensive mathematical analysis. In this paper, a simpler practically feasible FLC is designed that selects the appropriate bandwidth for the torque hysteresis controller to optimize the ripple level in the developed torque and hence, to improve the motor speed response.

A complete simulation model for the proposed drive is developed using MATLAB/Simulink. The effectiveness of the proposed drive is verified at different dynamic operating conditions by both simulation and experimental results.

II. Direct Torque Control Induction Motor Drive

Direct torque control (DTC) is one of the method used in variable frequency drives to control the torque (and thus finally the speed) of three phase AC electric motors. The name direct torque control is derived from the fact that 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. The principle of DTC method is to select one of the inverters namely six voltage vectors and two zero vectors in order to keep the stator flux and torque within a hysteresis band around the demand flux and torque magnitudes. The basic DTC scheme is shown in Fig.1. [7].

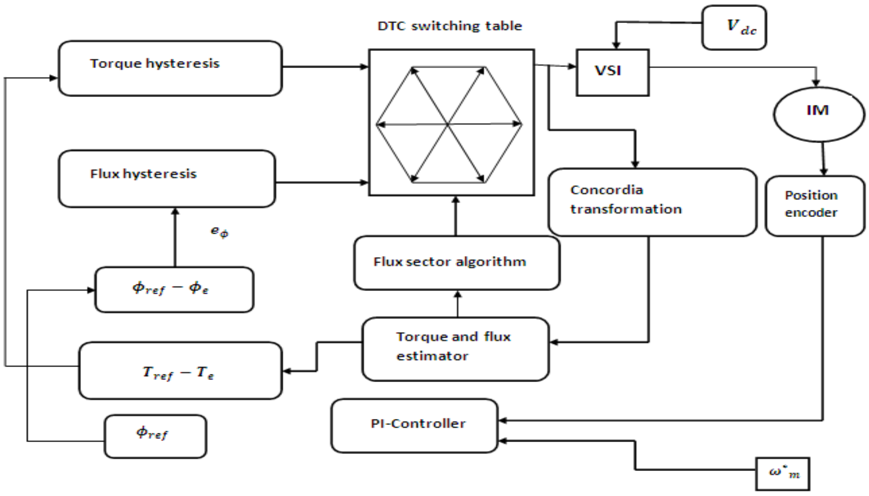


Fig. 1. Conventional DTC scheme for IM drive

III. Dtc Modelling Of Im For

3.1. Dynamic modelling of IM

Based on the three inputs (output digit of torque hysteresis controller, output digit of flux linkage hysteresis controller, and sector number where stator flux-linkage space vector is positioned), the DTC switching table produces the logic signals S_a, S_b and S_c. These logic signals are used to trigger the switches of the three-phase voltage source inverter (VSI) [8]. The possible six active combinations of these logic signals and the corresponding active input voltage vectors of the inverter (V1 to V6) are shown in Fig. 2. The three phase output voltage of VSI, which is the input to the stator of IM, is given by [7].

$$V_{sa} = (\frac{V_{dc}}{3})(2S_a - S_b - S_c) \quad (1)$$

$$V_{sb} = (\frac{V_{dc}}{3})(2S_b - S_c - S_a) \quad (2)$$

$$V_{sc} = (\frac{V_{dc}}{3})(2S_c - S_a - S_b) \quad (3)$$

Where, V_{dc} stands for dc link inverter voltage. The real V_{Sd} and imaginary V_{Sq} components of the stator voltage vector are obtained by using the Concordia transformation as [7].

$$\begin{bmatrix} V_{Sd} \\ V_{Sq} \end{bmatrix} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{-3}}{2} \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \quad (4)$$

From this real and imaginary voltage components, direct and quadrature components for stator and rotor flux are derived as [9]:

$$\phi_{sd} = [V_{sd} - i_{sd} R_s] \frac{1}{S} \quad (5)$$

$$\phi_{sq} = [V_{sq} - i_{sq} R_s] \frac{1}{S}$$
(6)

$$\phi_{rd} = [\omega\phi_{rq} - i_{rd} R_r] \frac{1}{S} \quad (7)$$

$$\phi_{sd} = [\omega\phi_{rd} - i_{rd} R_r] \frac{1}{S} \quad (8)$$

Stator and rotor current equations in the form of d-q axis are as below [9]:

$$i_{sd} = \phi_{sd} \left(\frac{L_r}{L_x}\right) - \phi_{rd} \left(\frac{L_m}{L_x}\right) \quad (9)$$

$$i_{sq} = \phi_{sq} \left(\frac{L_r}{L_x}\right) - \phi_{rq} \left(\frac{L_m}{L_x}\right) \quad (10)$$

$$i_{rd} = \phi_{rd}\left(\frac{L_s}{L_x}\right) - \phi_{sd}\left(\frac{L_m}{L_x}\right) \quad (11)$$

$$i_{rq} = \phi_{rq}\left(\frac{L_s}{L_x}\right) - \phi_{sq}\left(\frac{L_m}{L_x}\right) \quad (12)$$

Where, $L_x = L_s L_r - {L_m}^2$

Now, stator current is estimated by using park transformation as:

$$\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \quad (13)$$

IV. Stator Voltage And Flux

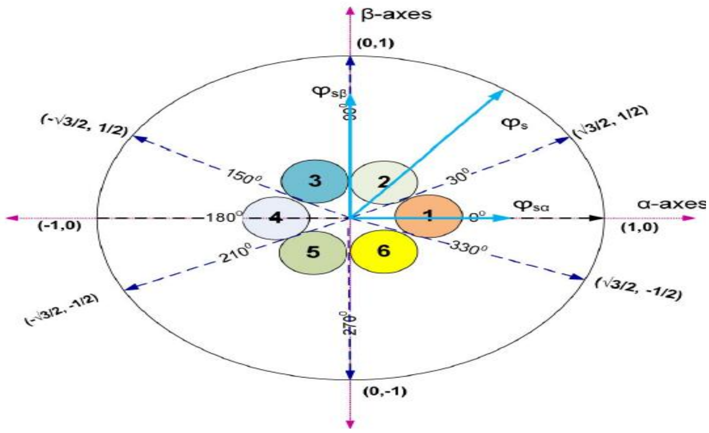


Fig. 2. Stator flux-linkage vector with six sectors.

Generally, the stator flux linkage can be obtained from the stator voltage vector as [1].

$$\Phi_s = \frac{1}{T_N}\int_0^t (V_s - R_s I_s)\, dt + \Phi_{s0}$$

(14)

Neglecting stator resistance Rs, it may be simplified as

$$\Delta_{\Phi s} = V_s\, \Delta t \quad (15)$$

$\Delta_{\Phi s}$ presents the change in stator flux caused by the application of an inverter voltage vector V_s , Φ_{s0} is the stator flux linkage at t = 0. The electromagnetic developed torque in IM is given by [8].

$$T_e = P\frac{L_m}{L_s L_r}|\Phi_s||\Phi_r| \sin\theta_{sr}$$

(16)

In steady state,$|\phi_r|$ and $|\phi_s|$ are almost constant and T_e depends on the torque angle θ_{sr}.

4.1. Flux, Torque and Angle Estimator

For the DTC scheme, the motor-developed torque and stator flux linkage are estimated as [1].

$$T_e = \frac{3}{2}P[\phi_{sd} i_{sq} - \phi_{sq} i_{sd}] \quad (17)$$

$$\phi_s = \sqrt{({\phi_{sd}}^2 + {\phi_{sq}}^2)} \quad (18)$$

As shown in Fig. 1, these estimated values of torque and flux are compared with the corresponding reference values and the error signals are delivered to the respective hysteresis controllers. On the basis of the magnitude of the error signals and allowable bandwidth, each hysteresis controller produces a digit. Then, the position of the stator flux-linkage space vector is evaluated as:

$$\theta_s = \tan^{-1}\left(\frac{\phi_{sq}}{\phi_{sd}}\right)$$

(19)

Using this angle, the flux sector number (1 to 6) is determined by using the flux sector algorithm [1]. Therefore, two digits produced by hysteresis controllers and one by flux position are collectively used to trigger the switches of the VSI which selects the appropriate voltage vector by using the classical DTC lookup table [10]. Fig. 2 shows the possible voltage vectors which are employed in the DTC scheme. The appropriate voltage vector in each sampling period is selected in such a way that the torque and flux remain within their respective band limits.

V. Direct Torque Control Principal

5.1. Flux hysteresis comparator

In DTC, stator flux is forced to follow a circular path by limiting its magnitude within its hysteresis band. This can be done by increasing the flux magnitude when it touches the lower limit of the hysteresis band and decreasing it when it touches the upper limit. To know whether the stator flux is needed to be increased or decreased, the relative magnitude of the actual flux compared to the reference flux had to be known. This comparative action can be done by occupying a two level hysteresis comparator as shown in Fig. 3. Flux error status equal to 1 indicates that the stator flux touches its upper band which means that the actual flux needs to be increased and vice versa. Therefore, if increase in stator flux is required, then the flux error status $d\phi = 1$ and if a stator flux decrease is required, then $d\phi = 0$.

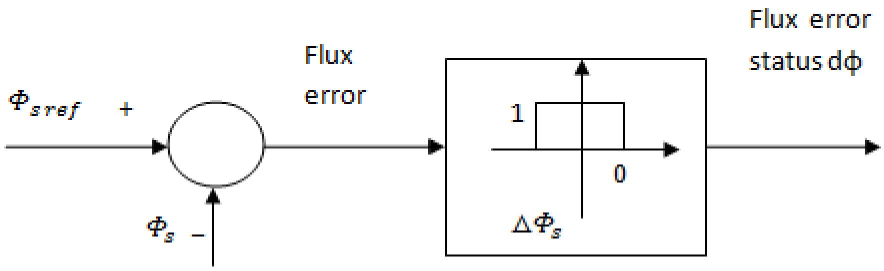


Fig.3. Two level flux hysteresis comparator

5.2. Torque hysteresis comparator

In DTC, at every switching period, the voltage vectors are selected to keep the electromagnetic torque within its hysteresis band. Torque needs to be reduced when it touches its upper band and increased when it touches its lower band. For this purposes, three levels hysteresis comparator as shown in Fig. 4 has been employed. If a torque increase is required then $dT_e = 1$, if a torque decrease is required then $dT_e = -1$, and if no change in the torque is required then $dT_e = 0$. The dT_e is the notation correspond the output signal of three level hysteresis comparator. dT_eThere are two conditions to be considered. The resulting for dT_eanticlockwise rotation (forward direction) and for clockwise rotation (backward rotation) of the stator flux.

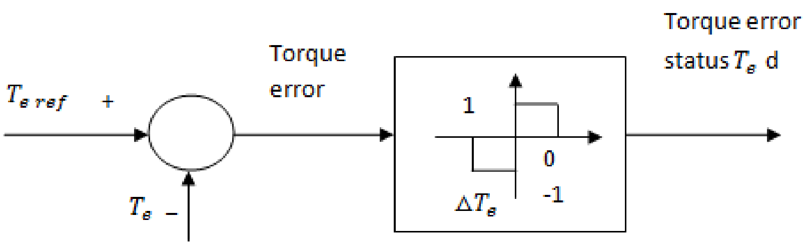


Fig.4. Three-level torque hysteresis comparator

5.3. Flux sector estimator

On the basis of the torque, flux hysteresis status and the stator flux switching sector, DTC algorithm selects the inverter voltage vector to apply to the induction machine from the Table 1. The outputs of the switching table are the settings for the switching devices of the inverter. Figure 2 shows the relation of inverter voltage vector and the stator flux switching sectors. Selection of sector depends on an angle θ , table I shows logic for selection of sector [11].

Table I

θ(Deg)	Sector
$360 < \theta \leq 30$	<1>
$30 < \theta \leq 90$	<2>
$90 < \theta \leq 150$	<3>
$150 < \theta \leq 210$	<4>
$210 < \theta \leq 270$	<5>
$270 < \theta \leq 330$	<6>

5.4. Switching Table

Switches of VSI are triggered by using the position of flux sector and two digits produced by hysteresis controller. These switches select the appropriate voltage vector by using classical DTC look up table.
According to the principal of operation of DTC, the selection of a voltage vector is made to maintain the torque and stator flux within the limits of two hysteresis bands. The selection of table for stator flux lying in the first sector of d-q plane is given in table II [10].

Table II

Sector		1	2	3	4	5	6
Flux	Torque						
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_7	V_0	V_7	V_0	V_7	V_0
	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_0	V_7	V_0	V_7	V_0	V_7
	1	V_5	V_6	V_1	V_2	V_3	V_4

VI. Design Of Flc For Torque Ripple Optimization

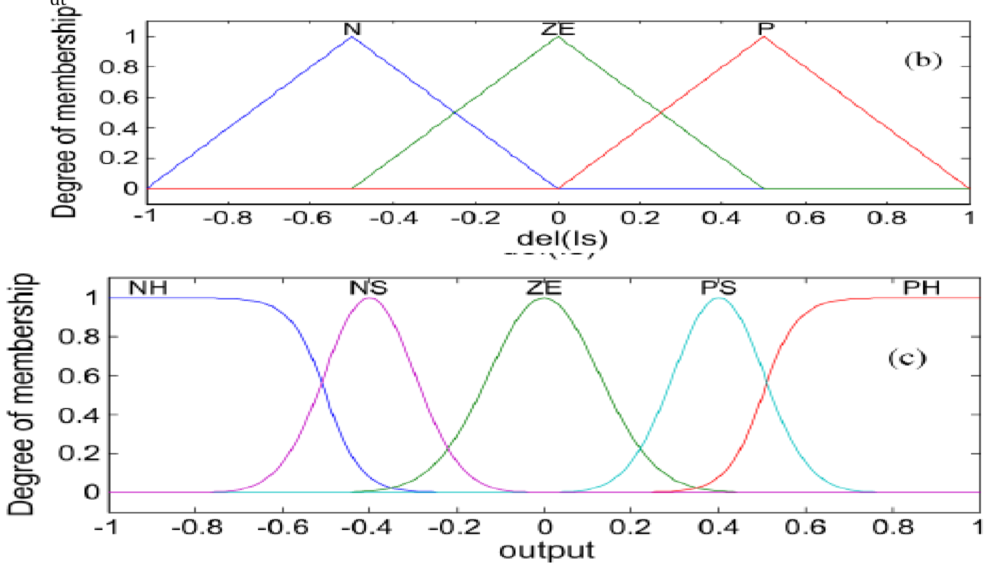
In this paper, a Mamdani-type FLC is developed to adapt the torque hysteresis band in order to reduce the ripples in the motor-developed torque. In conventional DTC technique, the amplitude of the torque hysteresis band is fixed. However, in this proposed scheme, the FLC controls the upper and lower limits of the torque hysteresis band on the basis of its feedback inputs. The fuzzy systems are universal function approximates [12]. The FLC is used as a nonlinear function approximator producing a suitable change in the bandwidth of the torque hysteresis controller in order to keep the torque ripples minimum. There are five membership functions for one input dT_e and three membership functions for another input dI_s. Automatically, there will be fifteen rules. For the inputs, we use triangular/trapezoidal membership functions in order to reduce the computational burden. However, for output we use Gaussian membership functions in order to change hysteresis bandwidth smoothly. The stator flux linkage is proportional to the stator current. Therefore, the motor-estimated torque variation dT_e and stator current variation dI_s over a sampling period are chosen as inputs to the FLC which can be defined by the following equations:

$$dT_e = T_e[n] - T_e[n-1] \quad (20)$$

$$dI_s = I_s[n] - I_s[n-1] \quad (21)$$

Where, $T_e[n]$ and $T_e[n-1]$ present the present and previous samples of motor-estimated torque, respectively.
The motor mechanical equation, neglecting the friction coefficient can be written as [7].

$$T_e - T_L = J\frac{d\omega_r}{dt} \quad (22)$$



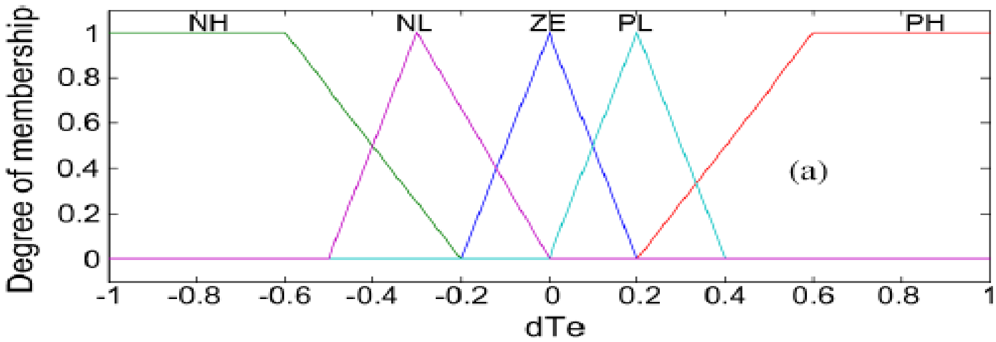


Fig. 5. Membership functions for input/output variables of FLC.

The fuzzy rules employed are as follows:

1) If $\boldsymbol{dT_e}$ is ZE and $\boldsymbol{dI_s}$ is N, then ΔHBT is ZE.
2) If $\boldsymbol{dT_e}$ is ZE and$\boldsymbol{dI_s}$ is ZE, then ΔHBT is ZE.
3) If $\boldsymbol{dT_e}$ is ZE and $\boldsymbol{dI_s}$ is P, then ΔHBT is ZE.
4) If $\boldsymbol{dT_e}$ is PL and $\boldsymbol{dI_s}$ is N, then ΔHBT is PS.
5) If $\boldsymbol{dT_e}$ is PL and $\boldsymbol{dI_s}$ is ZE, then ΔHBT is PH.
6) If $\boldsymbol{dT_e}$ is PL and $\boldsymbol{dI_s}$ is P, then ΔHBT is PH.
7) If $\boldsymbol{dT_e}$ is PH and $\boldsymbol{dI_s}$ is N, then ΔHBT is PH.
8) If $\boldsymbol{dT_e}$ is PH and $\boldsymbol{dI_s}$ is ZE, then ΔHBT is PH.
9) If $\boldsymbol{dT_e}$ is PH and $\boldsymbol{dI_s}$ is P, then ΔHBT is PH.
10) If $\boldsymbol{dT_e}$ is NL and $\boldsymbol{dI_s}$ is N, then ΔHBT is NH.
11) If $\boldsymbol{dT_e}$ is NL and $\boldsymbol{dI_s}$ is ZE, then ΔHBT is NH.
12) If $\boldsymbol{dT_e}$ is NL and $\boldsymbol{dI_s}$ is P, then ΔHBT is NS.
13) If $\boldsymbol{dT_e}$ is NH and $\boldsymbol{dI_s}$ is N, then ΔHBT is NH
14) If $\boldsymbol{dT_e}$ is NH and $\boldsymbol{dI_s}$*is* ZE, then ΔHBT is NH.
15) If $\boldsymbol{dT_e}$ is NH and $\boldsymbol{dI_s}$ is P, then ΔHBT is NH

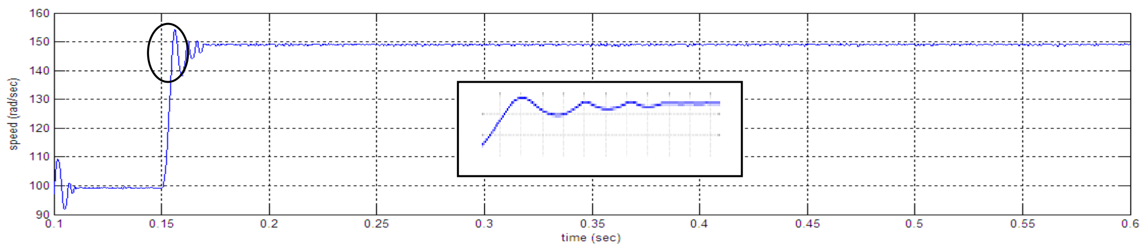
VII. Simulation Results

The simulation is carried out in Matlab-Simulink and typical results are reported here. The DTC method and the induction machine that used in the simulation works, have the parameters given in Table III.

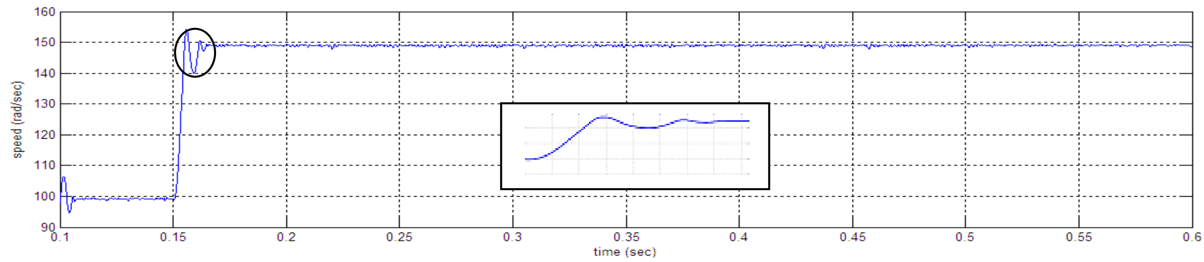
IM and Simulation Parameters	
Stator resistance(Ω)	6.5
Rotor resistance(Ω)	3.5
Mutual inductance(H)	$450.3e^{-3}$
Stator inductance(H)	$489.3e^{-3}$
Rotor inductance(H)	$489.3e^{-3}$
Poles	2
Inverter bus voltage(V)	380

7.1. Speed Analysis

Fig.6. show the simulation responses for a step change in command speed from 100 to 150 rad/s at t= 0.15 s. Figure shows the simulated speed response, with zoom-in view for interval of 0.15 to 0.18 s, using the conventional and the proposed DTC schemes . By using direct torque control technique we can control speed of the IM. Direct torque control scheme with fuzzy logic controller improves dynamic performance of speed as shown in fig. (b).The proposed scheme shows better response as compared to the conventional one in terms of speed ripple. From zoom in view it is seen that by using fuzzy logic controller speed undershoot is also reduced.



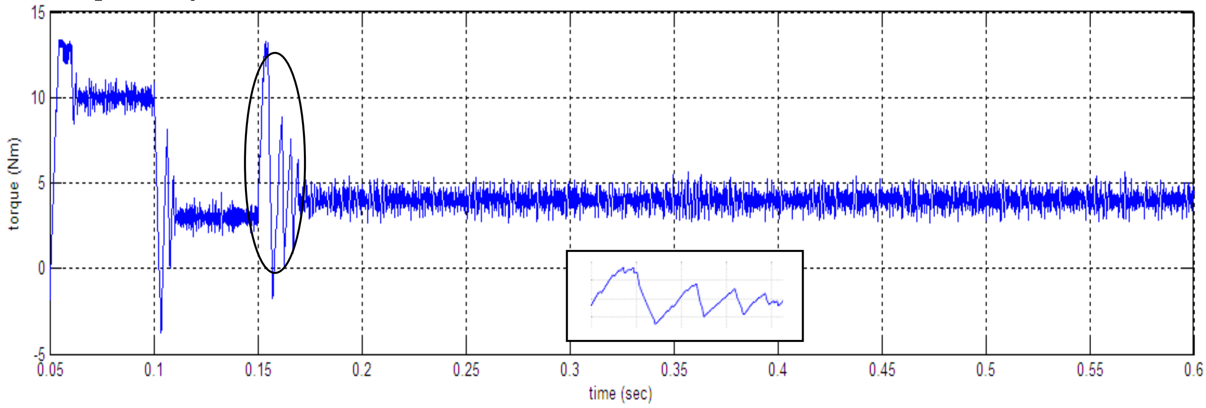
(a)



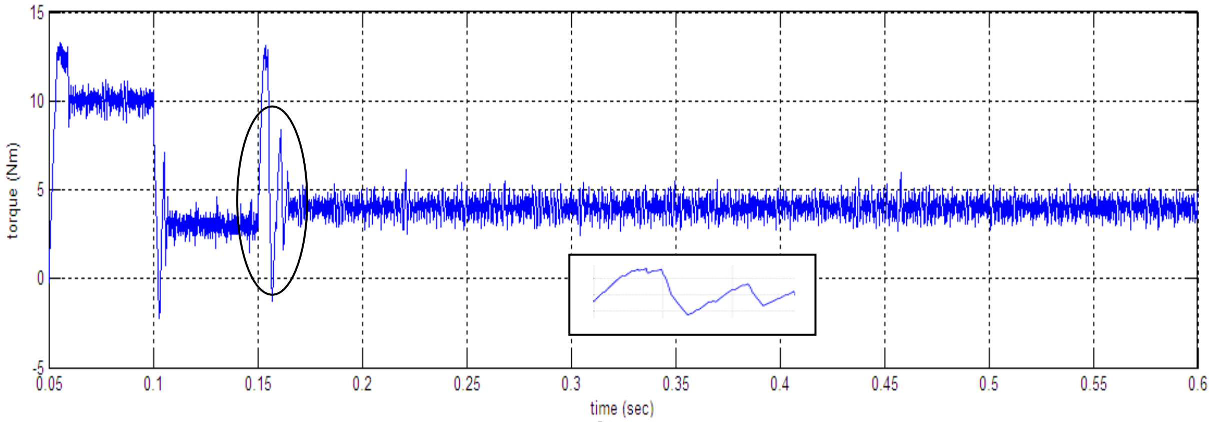
(b)

Fig. 6. Speed responses of the IM drive for a step change in command speed from 100 to150 rad/s . (a) Conventional DTC. (b) FLC-based DTC scheme.

7.2. Torque Analysis



(a)

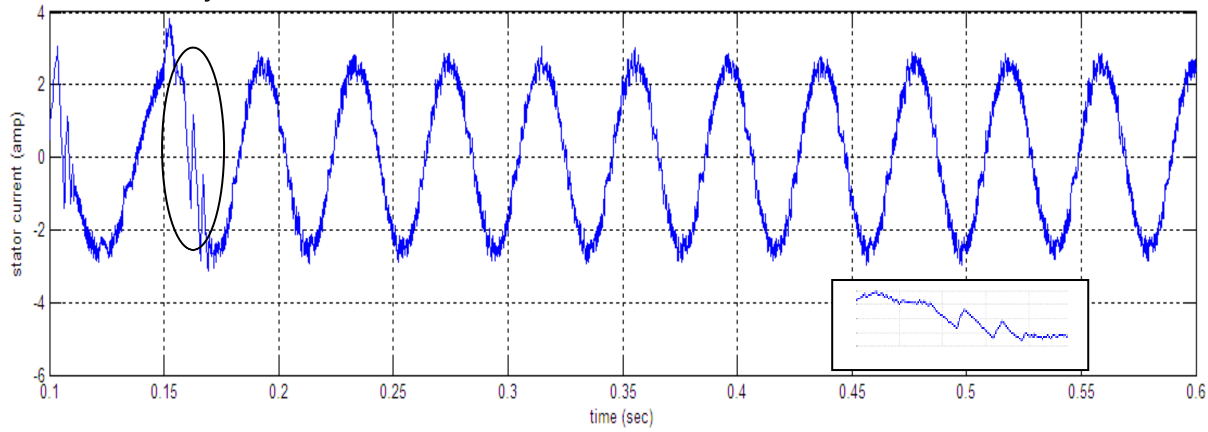


(b)

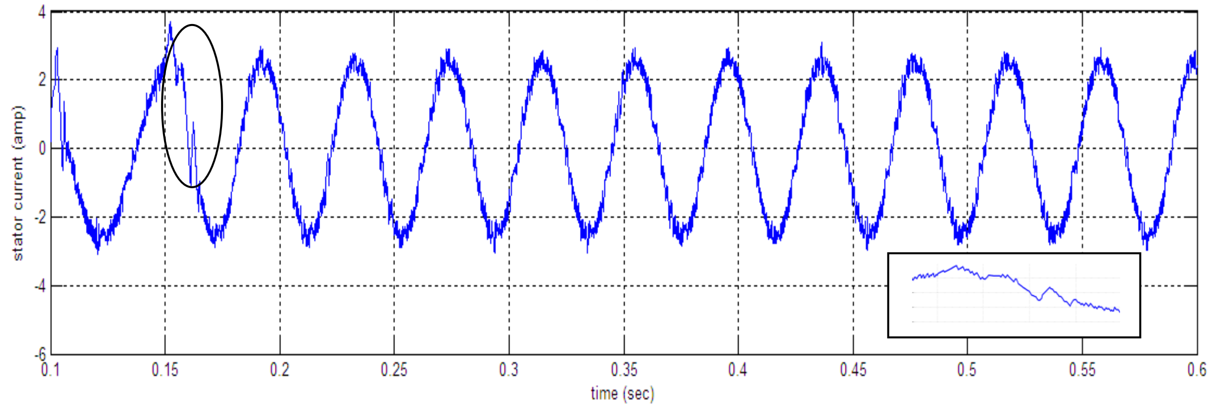
Fig.7.Developed torque responses of IM drive for step change in load from 0.3 to 0.8 N.m at speed from 100 to 150 rad. (a) Conventional DTC (b) FLC-based DTC scheme

Fig.(a) shows the corresponding torque responses for the conventional DTC scheme and fig.(b) shows torque response for proposed DTC scheme using fuzzy logic controller. The change in load is applied at a time of 0.3 sec. Fig.7 shows the simulated torque response, with zoom-in view for interval of 0.15 to 0.17 s, using the conventional and the proposed DTC schemes . The hysteresis band is limited to ± 1and ± 0.01 for torque and flux respectively. The zoom-in view of torque response clearly shows that torque ripples have been reduced considerably by the use of the proposed scheme.In proposed scheme the torque ripple has been reduced.

7.3. Current Analysis



(a)



(b)

Fig.8. Steady-state stator current response of the IM drive. (a) Conventional DTC. (b) FLC-based DTC scheme.

Fig. 8 shows the phase-a stator current of the conventional and proposed IM drives. The proposed scheme has lesser ripples in steady-state current. Figure shows the simulated current response, with zoom-in view for interval of 0.14 to 0.17 s, using the conventional and the proposed DTC schemes. By using fuzzy logic controller with DTC scheme ripples in current are reduced.

VIII. Conclusions

A novel FLC-based DTC scheme for IM drive has been presented in this paper. The FLC is used to adapt the bandwidth of the torque hysteresis controller in order to reduce the torque ripple of the motor. A performance comparison of the proposed FLC-based DTC scheme with a conventional DTC scheme has also been provided both in simulation .Comparative results show that the torque ripple of the proposed drive has considerably been reduced. The dynamic speed response of the proposed FLC-based DTC scheme has also been found better as compared to the conventional DTC scheme.

Optimization techniques such as Artificial Neural Network (ANN) Genetic algorithm (GA), Particle Swarm Optimization (PSO) and Advanced PSO can be used for the better performance analysis of induction motor by improving the training algorithm and fuzzy rule set.

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