Chapter 39
Implementation of Direct Torque Control for Matrix Converter Fed Induction Motor Drive Using Fuzzy Logic Controller

J. Karpagam, A. Nirmal Kumar, V. Kumar Chinnaiyan and M. Surya

Abstract Direct Torque Control (DTC) has emerged as a powerful tool to reduce the torque ripples. DTC is the strategy of selecting the proper stator voltage vectors to force the stator flux and developed torque within the prescribed band. However, the main disadvantage of conventional DTC is electromagnetic torque ripple. This paper aims to analyze the DTC to reduce the torque ripple in induction motor drive employing duty ratio fuzzy logic controllers. The DTC is combined with the Matrix Converter (MC) to give the advantages of the proposed method. Duty ratio controller is introduced to reduce the flux and torque ripples in place of hysteresis comparators. The simulations were carried out using Matlab/Simulink software package. Simulation result shows the effectiveness of drive performance, flux and torque responses.

Keywords Direct torque control · Induction motor drives · Matrix converters · Duty ratio fuzzy controller

39.1 Introduction

A matrix converter is a direct AC to AC converter in a single stage without any DC link. It consists of nine bidirectional switches. The advantages of MCs are inherent bidirectional power flow, sinusoidal input output waveforms, absence of dc link

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reactive components and controllable input power factor [1]. The objective of the matrix converter is to generate variable amplitude and variable frequency ac supply from the fixed amplitude and frequency ac supply. The main condition is that any input phase should not be short circuited and any output phase should not be open circuited [2].

A different control technique is used to control the speed of the induction motor drive. A new class of control technique called direct torque control is introduced to reduce the electromagnetic torque ripples in drives. It is considered as an alternative to field oriented control technique [3]. DTC is the method used to directly control the torque and flux of a drive by the proper selection of the space vectors for converters. The main advantage of DTC is its simple structure, no coordinate transformations is required, no need for separate pulse width modulator, PWM generation are not required. The DTC method has become one of the high performance control strategies for AC machines to provide a very fast torque and flux control. For such advanced reasons, the combination of MC with DTC method is effectively possible. Even though, DTC has more advantages, it uses two hysteresis controllers for stator flux and torque which produces steady state ripple in flux and torque responses. To overcome this problem, hysteresis controller is replaced by duty ratio fuzzy logic controller.

The work presented in this paper mainly focuses on modeling of matrix converter fed induction motor drive and the design of fuzzy logic controller for torque and flux control with the corresponding membership functions [4]. Results are obtained for loaded conditions using Matlab/Simulink software to validate the performance of the proposed controller. The obtained results exhibit the better performance (reduced ripples) than that of the other methods.

39.2 Direct Torque Control

39.2.1 Conventional DTC

The principle of direct torque control is to directly select the voltage vectors according to the difference between reference and actual value of torque and flux linkage. The most opportune converter switching state is selected at any instant based on the output signals of a flux and torque comparators and with the knowledge of the position of the stator flux space vector [5].

The three phase quantities are treated using single equation known as space vector.

$$V_s = \frac{2}{3}[V_a(t) + V_b(t)e^{\frac{j2\pi}{3}} + V_c(t)e^{\frac{j2\pi}{3}}] \tag{39.1}$$

In the implementation of SVM, a rotating space vector will emulate a physical signal to determine each switching period to generate a time averaged sine wave

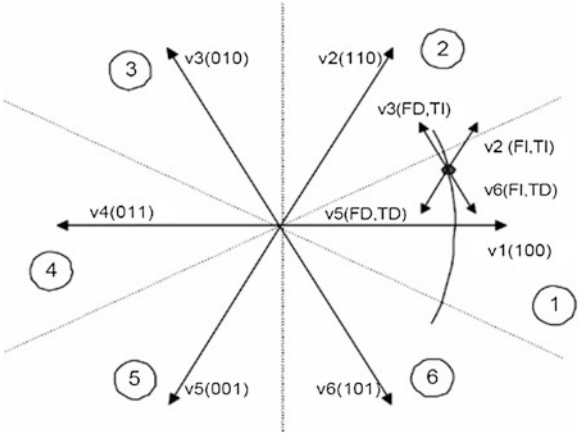

Fig. 39.1 Space vector representation of matrix converter

signal at the output of MC. The space vector travels through six sectors as shown in Fig. 39.1 each of which are 60°. Vectors 0 and 7 are on the origin called zero vectors and vectors 1–6 are called non-zero vectors.

The DTC technique allows to independently control the stator flux and the electromagnetic torque at the same time. If the reference value of the stator flux and torque are assumed, the estimated values are calculated from the stator currents and voltages. If the stator Ohmic drops are neglected, the stator voltage impresses directly the stator flux in accordance with the Eqs. (39.2)–(39.3) as follows:

$$V_s = \frac{d\psi_s}{dt} \tag{39.2}$$

$$d\psi_s = V_s dt \tag{39.3}$$

Therefore the variation of the stator flux space vector due to the application of the stator voltage vector V_s during a time interval of Δt can be approximated as in Eq. (39.4) and the electromagnetic torque in induction motor is expressed in Eq. (39.5),

$$\Delta\psi_s = V_s \Delta t \tag{39.4}$$

$$T_e = \frac{3}{2} P(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}) \tag{39.5}$$

The decoupled control of the stator flux modulus and the torque is achieved by acting on the radial and tangential components respectively of the stator flux linkage in its locus. The radial component controls the stator flux vector amplitude while the tangential component controls the stator flux vector angular position and hence the torque. A good dynamic performance can be obtained by the selection of an appropriate inverter voltage vectors V_i and the reference values.

Table 39.1 DTC switching for voltage source inverter

Stator flux ($\theta^{\wedge}{}_s$)		1	2	3	4	5	6
$C_\psi = -1$	$C_T = -1$	$V_{2\text{-vsi}}$	$V_{3\text{-vsi}}$	$V_{4\text{-vsi}}$	$V_{5\text{-vsi}}$	$V_{6\text{-vsi}}$	$V_{1\text{-vsi}}$
	$C_T = 0$	$V_{7\text{-vsi}}$	$V_{0\text{-vsi}}$	$V_{7\text{-vsi}}$	$V_{0\text{-vsi}}$	$V_{7\text{-vsi}}$	$V_{0\text{-vsi}}$
	$C_T = 1$	$V_{6\text{-vsi}}$	$V_{1\text{-vsi}}$	$V_{2\text{-vsi}}$	$V_{3\text{-vsi}}$	$V_{4\text{-vsi}}$	$V_{5\text{-vsi}}$
$C_\psi = 1$	$C_T = -1$	$V_{3\text{-vsi}}$	$V_{4\text{-vsi}}$	$V_{5\text{-vsi}}$	$V_{6\text{-vsi}}$	$V_{1\text{-vsi}}$	$V_{2\text{-vsi}}$
	$C_T = 0$	$V_{0\text{-vsi}}$	$V_{7\text{-vsi}}$	$V_{0\text{-vsi}}$	$V_{7\text{-vsi}}$	$V_{0\text{-vsi}}$	$V_{7\text{-vsi}}$
	$C_T = 1$	$V_{5\text{-vsi}}$	$V_{6\text{-vsi}}$	$V_{1\text{-vsi}}$	$V_{2\text{-vsi}}$	$V_{3\text{-vsi}}$	$V_{4\text{-vsi}}$

The Conventional DTC (CDTC) has three main parameters such as stator flux (ψ_s), torque (T_e) and the position of stator flux ($\hat{\theta_s}$). There are two different loops corresponding to the magnitudes of the stator flux and torque. The DTC requires flux and torque estimations, which are performed by means of two different phase currents and the states of the inverter [6]. The torque and the stator flux are estimated and compared with the corresponding reference values before passing the hysteresis comparator. The resulting values of flux and torque are fed into the two level and three level hysteresis comparators respectively. The outputs from the comparators of the stator flux (C_ψ) and torque (C_T) comparators with the position of the stator flux are used as inputs of the look up Table 39.1. According to the DTC principle, the most suitable space vector is selected among eight vectors in order to maintain the torque and the flux values within the prescribed hysteresis band from Table 39.1.

The DTC for MC was developed from the CDTC for VSI. Based on the optimum inverter vector which is selected for CDTC from VSI and some other parameters, the corresponding switching pattern will be determined for MC. At any instance, the magnitude and direction of MC output vectors depends on the position of the input line voltage vectors V_i. Once the position of V_i is determined, then only two among six switching configurations, which have the same sector as V_i does in its space vector, are acceptable. The average value of sin φ_i (φ_i is the angle between the input current vector and the corresponding input line voltage vector) is employed as the third parameter to determined one final switching configuration. The hysteresis comparator directly controls this variable. The schematic of the DTC method using the matrix converter fed induction motor is represented in Fig. 39.2.

From the voltage vector selected in the Table 39.1, the sin φ_i and the sector of the input voltage, the corresponding voltage vector is selected from Table 39.2. For example, with $C_T = +1$, $C_\psi = -1$ and the stator flux in sector 1, the suitable voltage vector selected from Table 39.1 is $V_{6\text{-vsi}}$ for a given switching period. Then, with the chosen VSI voltage vector $V_{6\text{-vsi}}$, $C_\varphi = +1$ and the input voltage vector in sector 2, finally the opportune voltage vector selected from Table 39.2 is -5_{MC}.

The main drawback of the CDTC is torque ripple. The reason is that the selected voltage vector is applied for the complete switching period regardless of the magnitude of the torque error, resulting in a wide torque hysteresis band. A better drive performance can be achieved by varying the duration of applying the selected

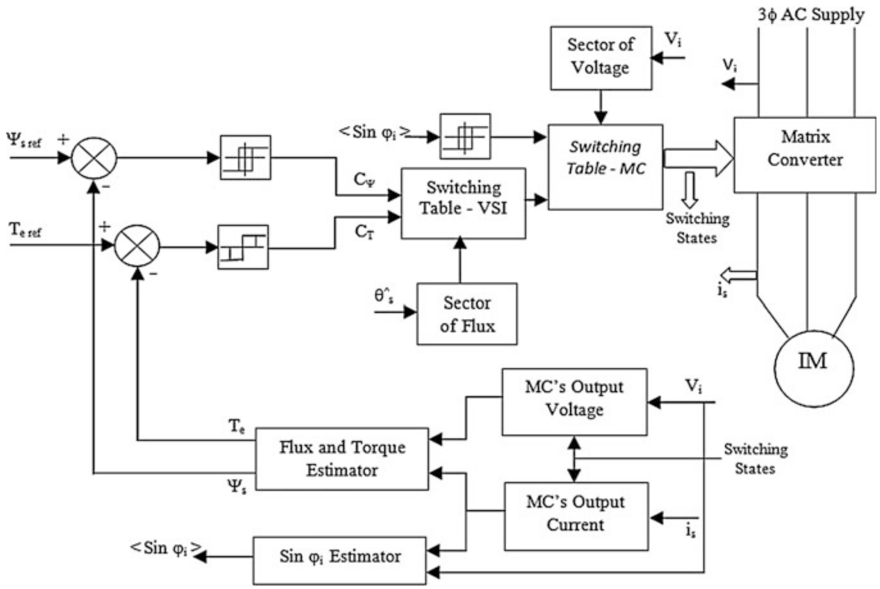

Fig. 39.2 Block diagram of direct torque control with MC

voltage vector during each switching period according to the magnitude of the torque error and the position of the stator flux, which will result in a small torque hysteresis band and hence lesser torque ripple [5]. Hence the selected non-zero voltage vector is applied for a part of the switching period and remaining period is with zero voltage vector. The ratio of the portion of the switching period for which a non-zero voltage vector is applied defined as duty ratio. Fuzzy logic is an appropriate choice for the design of the duty ratio controller.

39.3 Proposed Duty Ratio Fuzzy Logic Controller

The CDTC possess the good dynamic performance but shows quite poor performance in steady state since the crude voltage selection criteria gives rise to high ripple levels in flux linkage, torque and stator current. Fuzzy control is the best way for controlling the system without the need for knowing the mathematical model of the system [3]. The DTC performance can be improved by a complimentary use of fuzzy regulators are proposed. The two hysteresis controllers of CDTC are replaced with two fuzzy regulators.

From the observations obtained by examining the CDTC behavior, two sets of fuzzy rules were formulated; one when the flux magnitude is less than its reference value and the second when the flux magnitude is greater than the reference value. The inputs to each rule set are the magnitude of the torque error and the position of

Table 39.2 Switching table for DTC using matrix converter

V_i	1		2		3		4		5		6	
C_φ	+1	−1	+1	−1	+1	−1	+1	−1	+1	−1	+1	−1
$V_{1\text{-vsi}}$	-3_{mc}	$+1_{mc}$	$+2_{mc}$	-3_{mc}	-1_{mc}	$+2_{mc}$	$+3_{mc}$	-1_{mc}	-2_{mc}	$+3_{mc}$	$+1_{mc}$	-2_{mc}
$V_{2\text{-vsi}}$	$+9_{mc}$	-7_{mc}	-8_{mc}	$+9_{mc}$	$+7_{mc}$	-8_{mc}	-9_{mc}	$+7_{mc}$	$+8_{mc}$	-9_{mc}	-7_{mc}	$+8_{mc}$
$V_{3\text{-vsi}}$	-6_{mc}	$+4_{mc}$	$+5_{mc}$	-6_{mc}	-4_{mc}	$+5_{mc}$	$+6_{mc}$	-4_{mc}	-5_{mc}	$+6_{mc}$	$+4_{mc}$	-5_{mc}
$V_{4\text{-vsi}}$	$+3_{mc}$	-1_{mc}	-2_{mc}	$+3_{mc}$	$+1_{mc}$	-2_{mc}	-3_{mc}	$+1_{mc}$	$+2_{mc}$	-3_{mc}	-1_{mc}	$+2_{mc}$
$V_{5\text{-vsi}}$	-9_{mc}	$+7_{mc}$	$+8_{mc}$	-9_{mc}	-7_{mc}	$+8_{mc}$	$+9_{mc}$	-7_{mc}	-8_{mc}	$+9_{mc}$	$+7_{mc}$	-8_{mc}
$V_{6\text{-vsi}}$	$+6_{mc}$	-4_{mc}	-5_{mc}	$+6_{mc}$	$+4_{mc}$	-5_{mc}	-6_{mc}	$+4_{mc}$	$+5_{mc}$	-6_{mc}	-4_{mc}	$+5_{mc}$

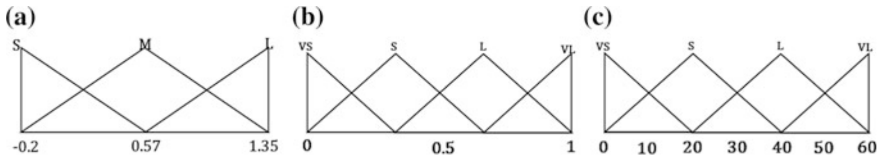

Fig. 39.3 Membership functions **a** torque error, **b** duty cycle, **c** flux angle

the stator flux; the output is the duty ratio [7]. Based on the universe of discourse of input and output membership functions such as very small, small, medium, very large and large as shown in Fig. 39.3, twelve rules are formulated in each set associated with the specific flux error sign.

With the selected three membership functions for torque error (input), four membership functions for flux angle (input) and duty ratio (output), the fuzzy rules are formed [7]. Generally the duty ratio is proportional to the torque error, since the rate of change of torque is proportional to the angle between the stator flux and the applied voltage vector, the duty ratio depends also on the flux position within each sector. The use of two fuzzy sets is due to the fact that when the stator flux is greater than its reference value a voltage vector that advance the stator flux vector by two sectors is applied which result in a higher rate of change of the torque compared to the application of a voltage vector that advance the stator flux vector by one sector when the stator flux linkage is less than its reference value.

39.4 Results and Discussion

CDTC and DTC with the duty ratio fuzzy control for the induction machine were simulated. The simulation was run at various switching frequencies and the optimum value is found as 5 kHz and results are presented for the same. MATLAB fuzzy logic toolbox was used in the implementation of the duty ratio fuzzy controller. The membership functions and the fuzzy rules were adjusted using the simulation until an optimal torque ripple reduction is achieved. In both the CDTC and FDTC, the dynamic response of torque, flux and stator current are analyzed. The stator flux trajectories were also obtained. To compare the above said parameters, the load torque is varied in steps.

Figure 39.4a, b shows the torque response of the motor using CDTC and fuzzy DTC for a step change of the reference torque of 40 Nm respectively. In both the methods, the starting torque is high. The torque response reaches its steady state value in 0.1 s. The torque ripple is around 15 Nm in CDTC, while with fuzzy DTC it is reduced to 4 Nm, neglecting the overshoot in the torque values at the beginning of the each voltage sector. In CDTC, higher ripples are produced. But in the proposed duty ratio controller reduces the torque ripples and exactly follows the set values. The obtained result proves that the proposed method is more effective than

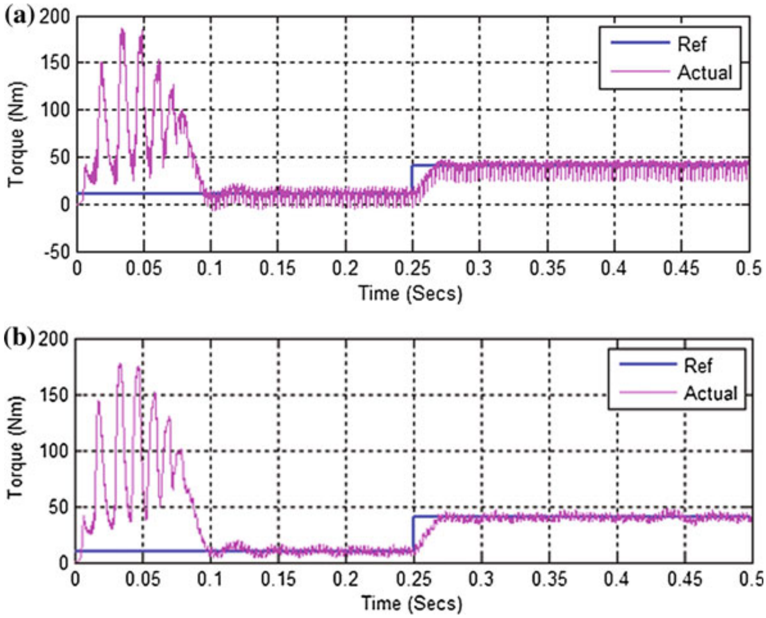

Fig. 39.4 Torque response of **a** conventional DTC, **b** fuzzy DTC

conventional method. Figure 39.5a, b shows the steady state stator current response of conventional and fuzzy DTC respectively. The fuzzy controller produces almost sinusoidal current waveform compared to conventional DTC which has more ripples. Figure 39.6a, b shows the stator flux for d and q axis of conventional and fuzzy DTC respectively. Similar to the current waveforms, stator flux is also sinusoidal when compared to conventional DTC.

Figure 39.7a, b shows the stator flux trajectory of conventional and fuzzy DTC for a step change in load torque. The flux vector describes that a trajectory is almost circular by keeping the torque and flux values are varied within their allowable tolerance band limits. While driving the motor in the projected stator flux paths, the torque ripples gets minimized and we can achieve the faster torque response. There is a dip in the stator flux magnitude at the beginning of the sector because the angle between the selected nonzero voltage vector and the stator flux is large when the stator flux vector lies in the beginning of the sector, so the selected vector does not act effectively in the longitudinal component of the flux vector to keep its magnitude close to its reference value.

The dynamic response of the proposed control scheme has been tested with sudden change in load torque such as decrease, increase and reversal for switching frequency of 5 kHz. It is observed that from Figs. 39.8 and 39.9, the torque shows a very good response and the current waveforms are almost sinusoidal immediately after the change in the torque command.

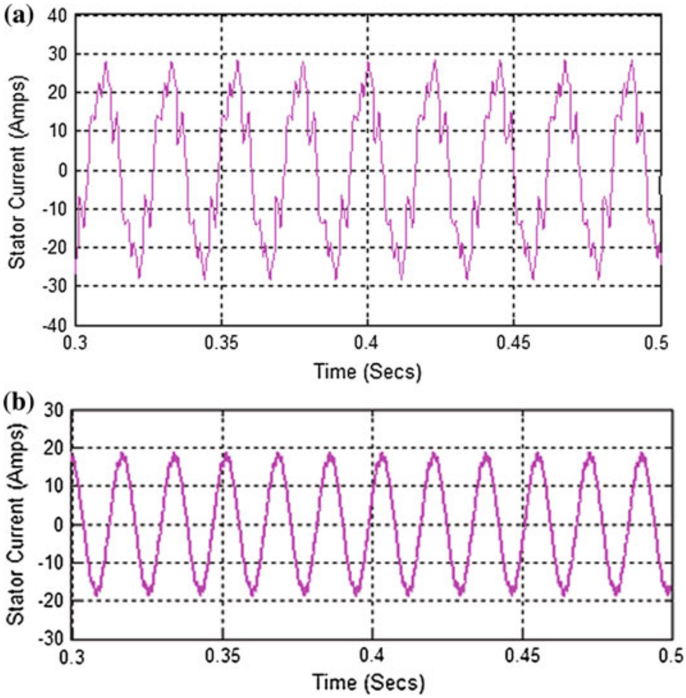

Fig. 39.5 Stator current of **a** conventional DTC, **b** fuzzy DTC

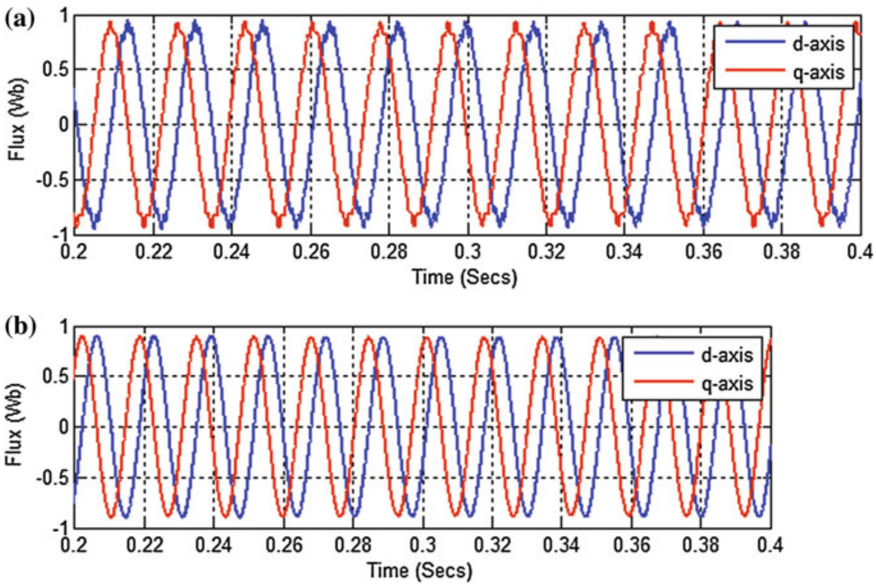

Fig. 39.6 Stator D and Q axis flux of **a** conventional DTC, **b** fuzzy DTC

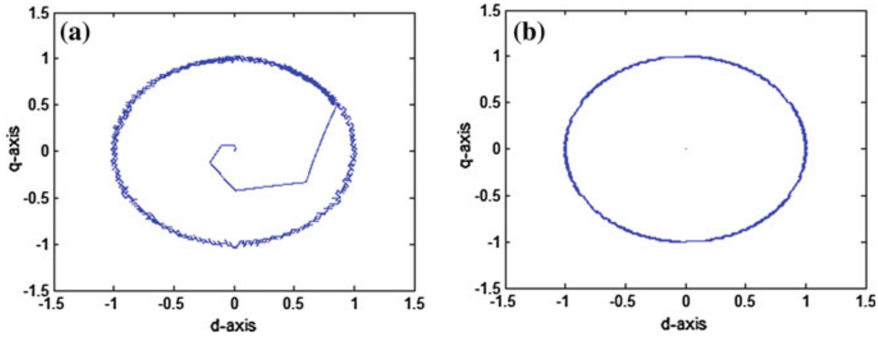

Fig. 39.7 Stator flux trajectory of **a** conventional DTC, **b** fuzzy DTC

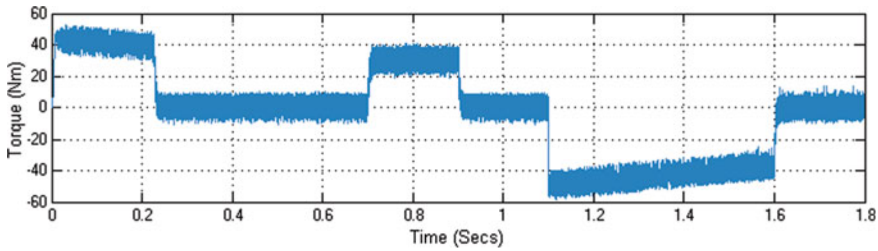

Fig. 39.8 Torque response of varying load torque

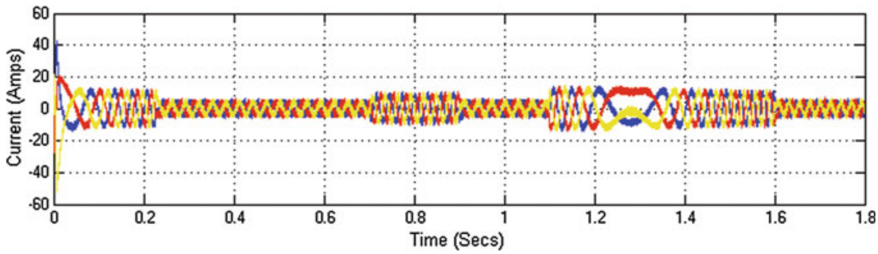

Fig. 39.9 Stator current

From the obtained results, it can be proved that the torque ripples are effectively reduced using the fuzzy controller. An improper selection of switching voltage vectors may results in undesired stator flux trajectory path, which increases the torque ripples. The simulation results suggest that proposed Fuzzy Logic Duty Ratio controlled DTC of induction machine can achieve precise control of the stator flux and torque. On comparison of results derived from simulation shows that Fuzzy Logic Duty Ratio DTC is superior to conventional DTC and minimizes the Torque ripple to large extent.

39.5 Conclusion

The MATLAB fuzzy logic toolbox is used in the implementation of the duty ratio fuzzy controller. Simulink is used to simulate the effect of the fuzzy controller on the performance of the DTC scheme and compare it to the conventional DTC. The use of fuzzy logic control reduces the computation burden by avoiding unnecessary complex mathematical modeling of the nonlinear systems and yields satisfactory results. The duty ratio fuzzy control improves the performance of the DTC at any given switching frequency without the need to change the frequency the terminals voltages, current and decides the voltage vector. The torque ripples are reduced by 26.2 % in fuzzy DTC compared to conventional DTC. The value of the duty ratio needs to be updated at each period in order to obtain the improved performance of the DTC drive. The duty ratio control reduces the stator current harmonics which intern reduces the torque ripple, the power losses and increase efficiency of the drive. The duty ratio control reduces the torque ripple in DTC induction motor drives and the same is verified by simulation results.

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