Minimization of Torque Ripple in DTC of Induction Motor Using Fuzzy Mode Duty Cycle Controller

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Abstract - Among all control methods for induction motor drives, Direct Torque Control (DTC) seems to be particularly interesting being independent of machine rotor parameters and requiring no speed or position sensors. The DTC scheme is characterized by the absence of PI regulators, coordinate transformations, current regulators and PWM signals generators. In spite of its simplicity, DTC allows a good torque control in steady state and transient operating conditions to be obtained. However, the presence of hysterics controllers for flux and torque could determine torque and current ripple and variable switching frequency operation for the voltage source inverter. This paper is aimed to analyze DTC principles, and the problems related to its implementation, especially the torque ripple and the possible improvements to reduce this torque ripple by using a proposed fuzzy based duty cycle controller. The effectiveness of the duty ratio method was verified by simulation using Matlab/Simulink software package. The results are compared with that of the traditional DTC models.

I. INTRODUCTION

More than a decade ago , direct torque control (DTC) was introduced to give a fast and a good dynamic torque response and can be considered as an alternative to the field oriented control (FOC) technique [1-3].

These control strategies are different in the operation principle but their objectives are the same. They aim both to control effectively the motor torque and flux in order to force the motor to accurately track the command trajectory regardless of the machine and load parameter variation or any external disturbances[4].

In DTC of induction motors it is possible to control the stator flux, and the developed electromagnetic torque by selecting optimum inverter switching modes[5].

Common disadvantages of the conventional DTC are high torque ripple and slow transient response to the step changes in torque during start-up. Several technique have been developed to improved the torque performance [5-10]. In classical DTC induction motor drive there are torque and flux ripples because none of the inverter switching vectors is able to produce the desired changes in both torque and stator flux. However other various techniques are used which can reduce the torque ripples in the developed electromagnetic torque and stator flux. Some of these techniques involve the usage of high switching frequencies or the change of the inverter topology , but it is also possible to use schemes which do not involve any of the mentioned technique, such as the duty ratio control [11].

In this paper a fuzzy controller is used to obtain a duty-ratio that can be used to minimize the torque ripple, simulation results show that the torque ripple is significantly reduced when compared with the classical DTC.

II. INDUCTION MOTOR MODEL

In stationary reference frame , space voltage vector of both stator and rotor of the machine are represented as follows

$$\overline{V_s} = r_s \cdot \bar{i}_s + \frac{d\overline{\varphi_s}}{dt} \quad ..(1)$$

$$0 = r_r \cdot \bar{i}_r + \frac{d\overline{\varphi_r}}{dt} - jw\overline{\varphi_s} \quad ..(2)$$

$$\varphi_s = L_s i_s + M i_r \quad ..(3)$$

$$\varphi_r = M \cdot i_s + L_r i_r \quad ..(4)$$

where r_s , and r_r are stator and rotor resistances , V_s is the stator space voltage vectors , $\overline{\varphi_s}$ and $\overline{\varphi_r}$ are stator and rotor flux respectively. w is the angular speed of the rotor.

III. VECTOR MODEL OF THE INVERTER OUTPUT VOLTAGE

In a voltage fed three phase , the switching commands of each inverter leg are complementary. So for each leg a logic state C_i (i=1 ,2 ,3) can be defined. C_i is 1 if the upper switch is commanded to be closed and 0 if the lower one in commanded to be closed (first). Since there are 3 independent legs there will be eight different states, so 8-different voltages. Applying the vector transformation described as [12].

$$V_s = \sqrt{\frac{2}{3}} \cdot V_d \cdot \left[C_1 + C_2 \cdot e^{\frac{j2\pi}{3}} + C_3 \cdot e^{\frac{j4\pi}{3}} \right] \quad ..(5)$$

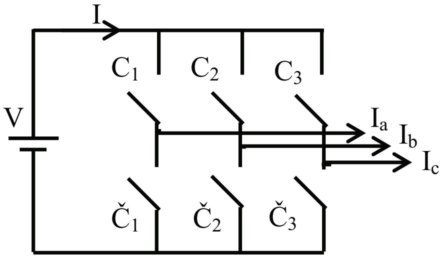


Fig.(1) Three phase voltage inverter

IV. DIRECT TORQUE CONTROL PRINCIPLES

It is well known that in the three phase induction motors the electromagnetic torque can be expressed as follows [11]

$$Te = \frac{3}{2} \cdot P \frac{L_m}{L_s \cdot L_r - L_m^{\,2}} \cdot \left|\overline{\varphi_s}\right| \cdot \left|\overline{\varphi_r}\right| \cdot \sin(\theta_s - \theta_r) \quad ..(6)$$

where θ_s ,and θ_r are the respective angles of stator and rotor fluxes respectively , P is the number of pair poles , and L_s , L_r ,L_m are the stator , rotor , and mutual reactance respectively. In equation (1) for simplicity , it is assumed that the stator voltage drop $r_s i_s$ is small and negligible, then the stator flux variation can be expressed as

$$\Delta\overline{\varphi_s} = \overline{V_s} \cdot \Delta t \quad ..(7)$$

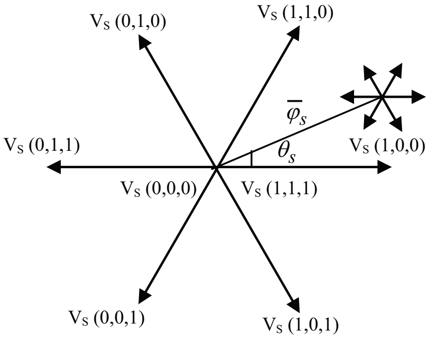


Fig. (2) Voltage Space Vector Representation

As shown in Fig.(2) the selection of the voltage vector depends on the position of stator flux linkage. The choice goal is to limit the flux and torque within the hysterics bands around their references values[13].With this type of corrector, in spite of its simplicity , one can easily control and maintain the end of the vector flux, in a circular ring[12].

The stator flux linkage command signal either increases or decreases in the controller circuit while the torque command signal either increases/decreases or it may stay constant. A table with 36 states can be constructed as it is shown in Table (1)[14].

Table (1) The switching table for the DTC

	sectors	1	2	3	4	5	6
flux	Torque						
$\Delta\varphi = 1$	$\Delta T = 1$	V_2	V_3	V_4	V_5	V_6	V_1
	$\Delta T = 0$	V_7	V_0	V_7	V_0	V_7	V_0
	$\Delta T = -1$	V_6	V_1	V_2	V_3	V_4	V_5
$\Delta\varphi = 0$	$\Delta T = 1$	V_3	V_4	V_5	V_6	V_1	V_2
	$\Delta T = 0$	V_0	V_7	V_0	V_7	V_0	V_7
	$\Delta T = -1$	V_5	V_6	V_1	V_2	V_3	V_4

V. STATOR FLUX AND TORQUE ESTIMATION

From the first principles of the DTC [15]

$$\varphi_{s\alpha} = \int \left(\overline{V_s} - \overline{I}_{s\alpha} \cdot r_s \right) \cdot dt \quad ..(8)$$

$$\varphi_{s\beta} = \int \left(\overline{V_s} - \overline{I}_{s\beta} \cdot r_s \right) \cdot dt \quad ..(9)$$

The components of the current ($I_{s\alpha}$, $I_{s\beta}$) and stator voltages ($V_{s\alpha}$, $V_{s\beta}$) are obtained by [1]

$$I_{s\alpha}=\sqrt{\frac{2}{3}}\cdot I_{sa} \quad ..(10)$$

$$I_{s\beta}=\frac{1}{\sqrt{2}}\cdot (I_{sb} -I_{sc}) \quad ..(11)$$

$$V_{s\alpha}=\sqrt{\frac{2}{3}}\cdot V_d \cdot (C_1 -\frac{1}{2}(C_2 +C_3)) \quad ..(12)$$

$$V_{s\beta}=\frac{1}{\sqrt{2}}\cdot V_d \cdot (C_2 - C_3) \quad ..(13)$$

Since α's , β's components are perpendiculars the stator flux linkage is given by

$$\varphi_s =\sqrt{\varphi^2{}_{s\alpha} + \varphi_{s\beta}{}^2} \quad ..(14)$$

and the flux angle is given by

$$\angle\overline{\varphi}_s =\tan^{-1}(\frac{\varphi_{s\beta}}{\varphi_{s\alpha}}) \quad ..(15)$$

The electromagnetic torque is given by

$$T_e =\frac{3}{2}\cdot P\cdot \left(\varphi_{s\alpha} \cdot i_{s\beta} -\varphi_{s\beta} \cdot i_{s\alpha}\right) \quad ..(16)$$

VI. DUTY RATIO CONTROL

The direct torque control has many promising features and advantages like absence of speed and position sensors, absence of coordinate transformation, reduced number of controller , minimal torque response time[5]. In spite of this advantages a major draw back of classical DTC is high torque and flux ripple because of none of the inverter switching vector is able to produce the exact stator voltage. However , if instead of applying a voltage vector for the entire switching period, it is applied for apportion of the switching period and the zero switching state is applied for the rest of the period in which the ripples can be reduced. This is defined as duty ratio control in which the portion of switching period for which a non zero voltage vector is applied is known as the duty ratio δ. and ratio (δ) is varied between 0 and 1.

VII. FUZZY LOGIC DTC CONTROLLER

Since the duty ratio during each switching state is a nonlinear function of a number of factors : torque error ($E_{te}=T_{ref}-T_e$) , flux error ($E_\psi= \overline{\varphi}_{ref} - \varphi_s$) and flux position (θ) , it is difficult to represent mathematically the relation between the three variables. The fuzzy logic control seems to be a reasonable choice to determine the duty ratio during each switching state[5]. The diagram of direct torque control with a fuzzy duty ratio control is shown in figure(3) below

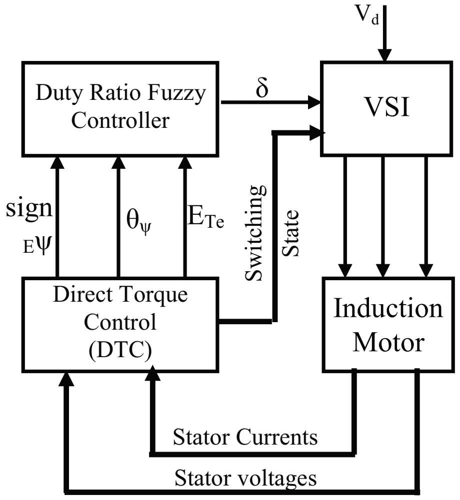


Fig.(3)Block diagram of fuzzy duty ratio control

In general, a fuzzy logic controller consist of three main parts : fuzzification , fuzzy reasoning (based on fuzzy rules) , and defuzzification. This system is known as Mamdani system shown in figure(4)

A Fuzzification

The torque error , and stator flux angle are given as input variables to fuzzy controller and output variable is duty ratio control (δ). The symbols used in memberships refers to the following linguistic term

Table(2) Linguistic term for torque error

Linguistic Term	Symbol
Small	S
Medium	M
Large	L

Table(3) Linguistic term for flux position

Linguistic Term	Symbol
Small	S
Medium	M
Large	L

Table(4) Linguistic term for duty ratio control

Linguistic Term	Symbol
Small	S
Medium	M
Large	L

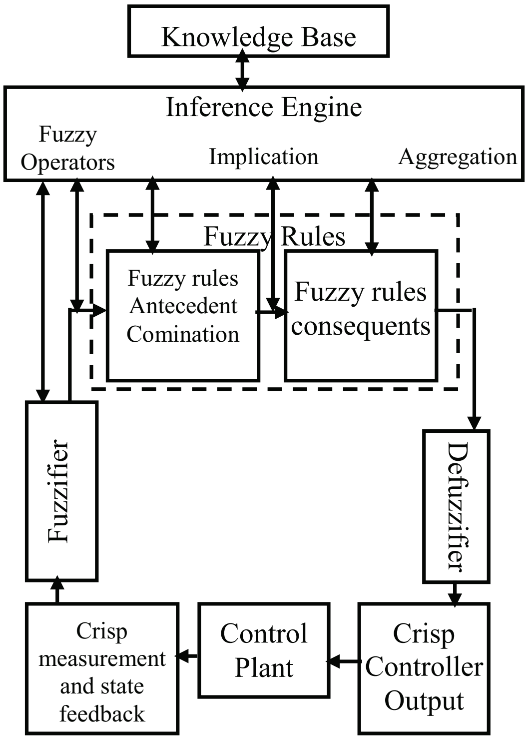
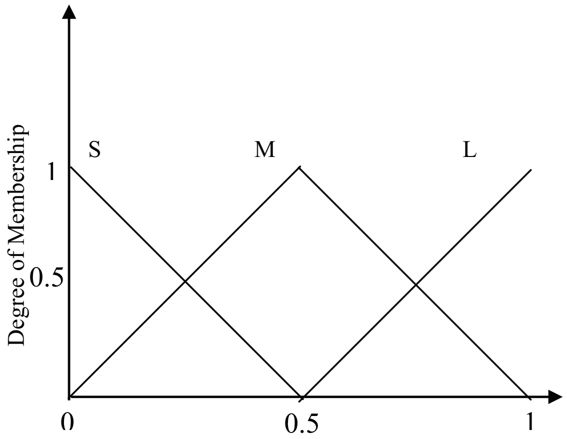
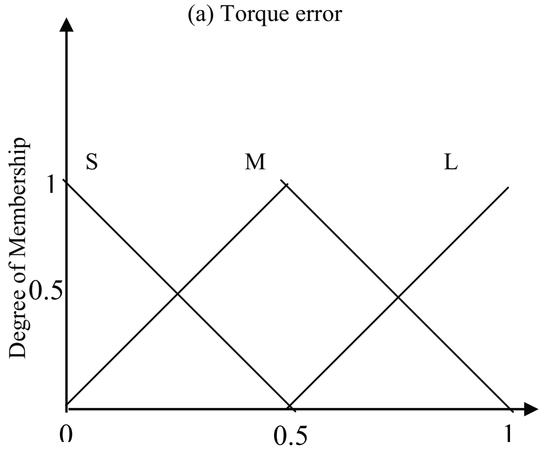


Fig. (4) Mamdani fuzzy logic controller

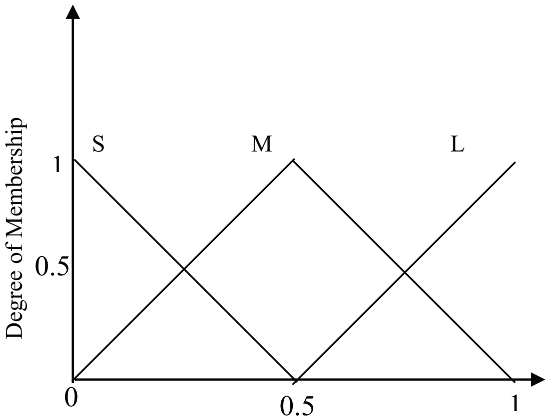
The input and output variable membership functions are shown in figure(5) below



(a) Torque error



(b) Flux Position



(c) Duty ratio

Fig.(5) Input and output membership functions

B Fuzzy reasoning and control rules

Fuzzy logic is well suitable to implement control rules that can only be expressed verbally for a system that can not be modeled with linear differential equations. Fuzzy rules are conditional statement that use fuzzy operators and membership functions to make control decisions[16]. Control rules are often expressed in the If-Then format. The ith rules R_i can be written as

R_i : If E_{te} is Ai and θ is B_i then δ is C_i

Where A_i , B_i ,and C_i denote the fuzzy set. i=1 to 9 , there are 9 reason rule .Combines the terms in the antecedent part of the fuzzy rules by using minimum operators, and the term in the consequent part with maximum operators.

Table(5) Fuzzy control linguistic roles for duty ratio control

E_ψ	E_{Te} / θ	S	M	L
Flux > Ref. Flux	S	S	S	M
	M	S	M	L
	L	S	M	L
Flux < Ref. Flux	S	S	M	L
	M	S	M	L
	L	M	L	L

C Defuzzification

To obtain the output of the fuzzy controller, the method of center of area (COA) is used. Using this method, the crisp output , δ is chosen as the center of area for the membership function of the overall implied fuzzy set B. for continuous output of the universe of discourse the center of area output is denoted by

$$\delta = \frac{\int_{\delta} \delta \cdot \mu_{\tilde{B}}(\delta) d\delta}{\int_{\delta} \mu_{\tilde{B}}(\delta) d\delta}$$

VIII. SIMULATION RESULTS

A simulink model for a DTC of induction motor drive system with fuzzy duty ratio based controller is implemented using the well known Matlab/Simulink software package, as shown in Fig. (6).

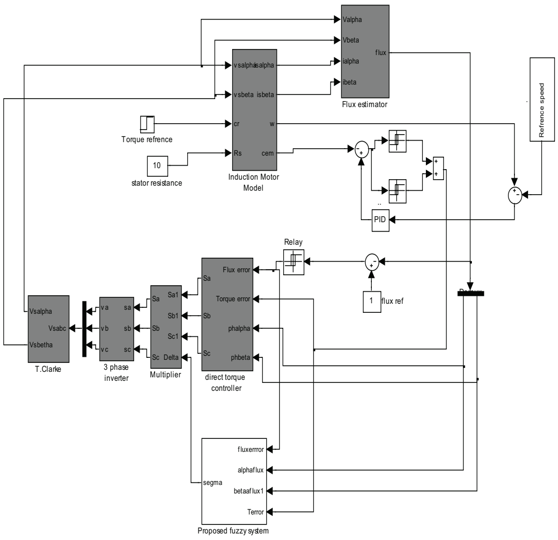


Fig.(6) Simulink model of the proposed system

The parameters of the induction motor used in this work are given in Table (6)

Table(6) Parameters of the Induction motor

Rated Voltage	380 V
Maximum Torque	15 N.m.
Poles	4
Rated Speed	1440 RPM
Stator Resistance	1.2 Ω
Rotor Resistance	1.8 Ω
Stator Leakage Inductance	0.1554 H
Rotor Leakage Inductance	0.1568 H
Mutual Inductance	0.15 H
Moment of Inertia	1.662

Figures (8) and (10) show the torque step response of the motor at 200 rad/sec for the classical DTC and the proposed one respectively. For the classical one , the torque ripple after loading rises to an average of ±18 N.m. while that for the proposed is ±10 N.m.

Figures (7) and (10) show the corresponding speed response for both cases. The stator current in classical and the proposed control scheme are shown in Figs. (9) and (12) respectively. The improvement in the speed response is well declared. For different loading conditions the torque, phase current and speed responses are shown through Figs.(13-18) for both the conventional DTC and the fuzzy based duty cycle controllers, which appreciates that the torque ripple decreases when the proposed scheme is used.

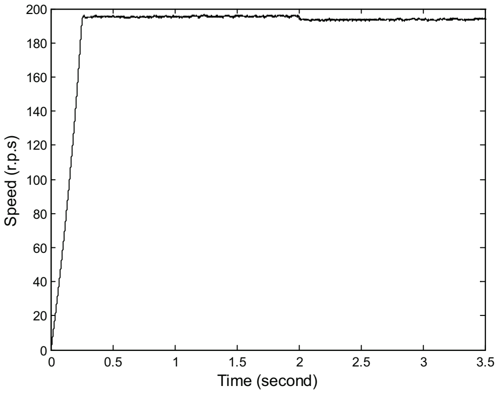


Fig. (7) Speed response for classical DTC with a step change of 5N.m. at 2 sec.

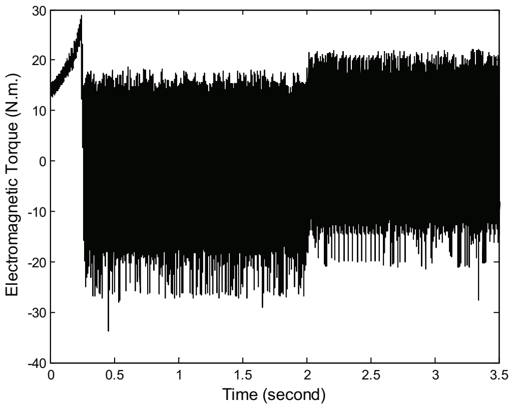


Fig.(8) Electromagnetic torque response with a step change of 5N.m. at 2 sec for classical DTC.

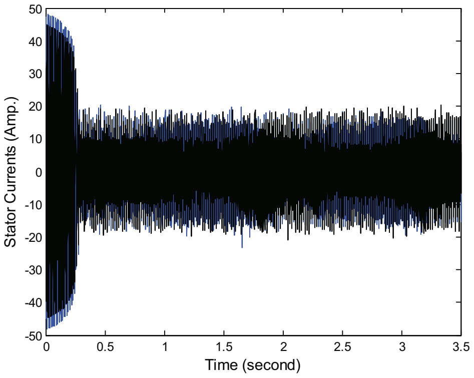


Fig.(9) Stator current for three phase induction machine for classical DTC

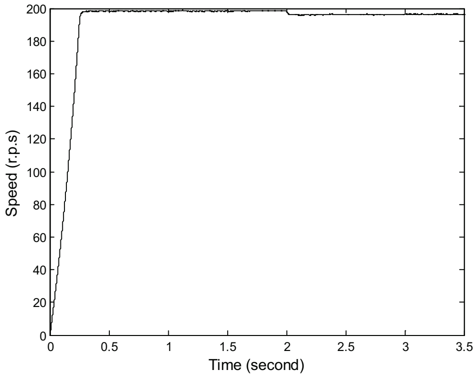


Fig.(10) Speed response for the proposed controller with a step change of 5N.m. at 2 sec

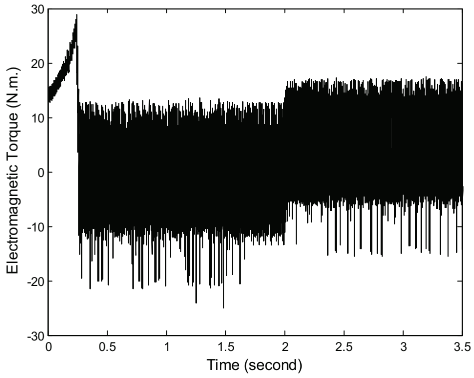


Fig.(11) Electromagnetic torque response for the proposed controller with a step change of 5N.m. at 2 sec.

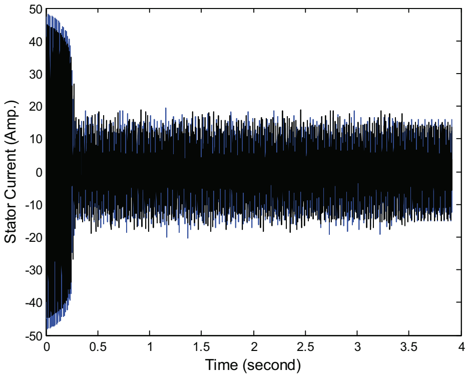


Fig.(12) Stator current for three phase induction machine for the proposed controller

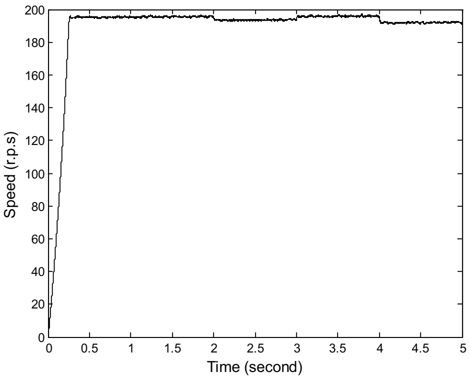


Fig.(13) Speed response for classical DTC with torque step change of 5N.m. at 2 sec. , 0 N.m. at 3 sec. and 10 N.m. at 4 second

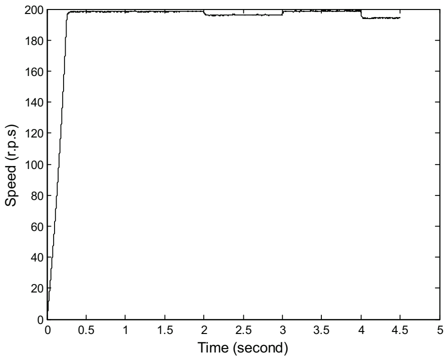


Fig.(16) Speed response for the proposed controller with torque step change of 5N.m. at 2 sec. , 0 N.m. at 3 sec. and 10 N.m. at 4 second

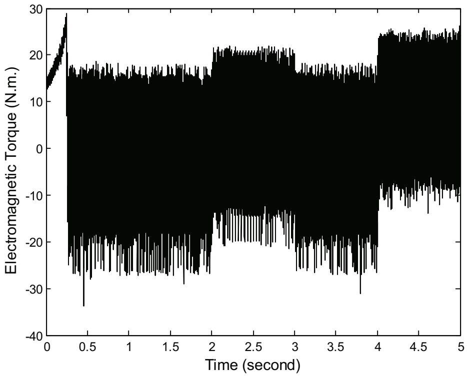


Fig.(14) Electromagnetic torque response for classical DTC with torque step change of 5N.m. at 2 sec. , 0 N.m. at 3 sec. and 10 N.m. at 4 second

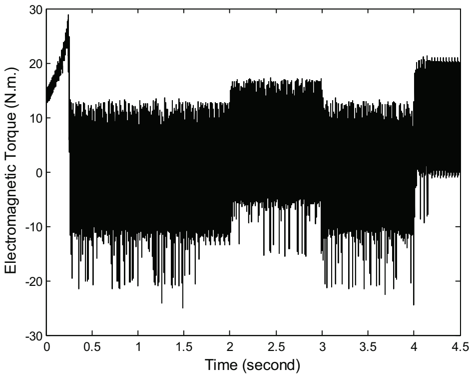


Fig. (17) Electromagnetic torque response for the proposed controller with torque step change of 5N.m. at 2 sec. , 0 N.m. at 3 sec. and 10 N.m. at 4 second

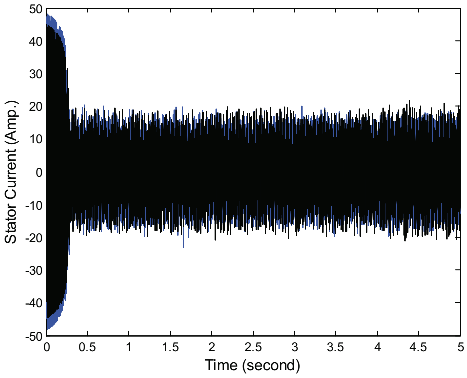


Fig.(15) Stator current for three phase induction machine with classical DTC with torque step change of 5N.m. at 2 sec. , 0 N.m. at 3 sec. and 10 N.m. at 4 second

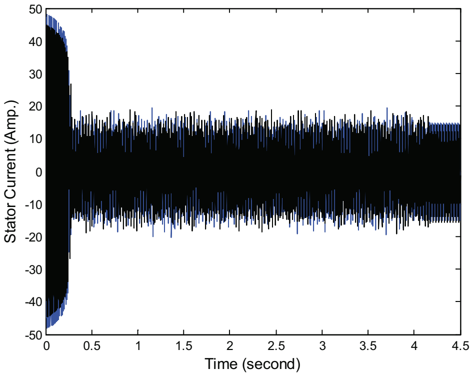


Fig.(18)Stator current for three phase induction machine for the proposed controller with torque step change of 5N.m. at 2 sec. , 0 N.m. at 3 sec. and 10 N.m. at 4 second.

IX. CONCLUSION

In this paper a fuzzy based duty cycle controller of induction motor have been proposed . An improved torque response was achieved with the fuzzy based duty cycle controller than the conventional DTC. The performance has been tested by simulations. The main improvements shown are reduction of torque and current ripples in transient and steady state response.

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