TORQUE RIPPLE REDUCTION IN DIRECT TORQUE CONTROL INDUCTION MOTOR DRIVE USING SVM AND FLDRC

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Abstract. Direct Torque Control (DTC) is a control technique used in AC drive systems to obtain high performance torque control. The conventional DTC drive contains a pair of hysteresis comparators, a flux and torque estimator and a voltage vector selection table. The torque and flux are controlled simultaneously by applying suitable voltage vectors, and by limiting these quantities within their hysteresis bands, de-coupled control of torque and flux can be achieved. However, DTC drives utilizing hysteresis comparators suffer from high torque ripple and variable switching frequency. This work aims at developing a DTC scheme for induction motor, with reduced toque ripple, using fuzzy logic duty ratio control (FLDRC) and Space Vector Modulation (SVM) techniques. From the simulation results shows that feeding electrical drive with proposed system greatly improves the drive performance. The performance of this control method has been demonstrated by simulations performed using a versatile simulation package, MATLAB/SIMULINK.

Keywords: DTC, Fuzzy logic, Duty ratio control, SVM, Induction motor, MATLAB/SIMULINK.

1. Introduction

The induction motor due to its well known advantages of simple construction, reliability, ruggedness, and low cost has found very wide industrial applications. These advantages are superseded by control problems when using an IM in industrial drives with high performance demands. Using DTC or direct self control (DSC) it is possible to obtain a good dynamic control of the torque without any mechanical transducer on the machine shaft. Thus DTC and DSC can be considered as "sensor less type" control techniques [1 - 6]. DSC is preferable in the high power range applications where a lower inverter switching frequency can justify higher current distortion. DTC is more suitable in the small and medium power range application .The basic concept of direct torque control induction motor drives is to control both stator flux and electromagnetic torque of the machine simultaneously. The direct torque control (DTC) based drives do not require the coordinate transformation between stationary frame and synchronous frame in comparison with the conventional vector controlled drives [7]. The name direct torque control (DTC) is derived by the fact that on the basis of the error between the reference and the estimated values of the torque and flux, it is possible to directly control the inverter states in order to reduce the torque and flux error within limits.

In duty ratio control technique, the voltage vector is not applied for the entire switching period; instead it is only applied for a portion of switching period and the zero switching state is applied for the rest of the switching period and with this the ripple is reduced considerably as compared to conventional DTC [8 - 13]. However, the basis of the SVM-DTC methodology is the calculation of the required voltage space vector to compensate the flux and torque errors exactly by using a predictive technique and then its generation using the SVM at each sample period.

In this paper, the simulations of different DTC schemes (Conventional DTC, DTC using duty ratio control technique and DTC using SVM) were carried out using MATLAB/SIMULINK simulation package and finally the results are compared based on their simulation results.

2. DTC Scheme

Figure 1 shows a simple structure of the conventional DTC for Induction motor drive. In DTC the reference to be applied is directly calculated from the equation of the load, usually an Induction Motor (IM). In the following, a short description of DTC is presented, just to introduce to its extension to multilevel VSI. Considering Park transform of IM equations, it is possible to write in equation (1), where φ_S is the stator flux, $\vec{U}_S$, $\vec{i}_S$ and r_S are the stator voltage, current and resistance respectively.

$$\frac{d\varphi_S}{dt} = \overrightarrow{U_S} - r_S \cdot \overrightarrow{i_S} \qquad (1)$$

Ignoring the contribution of the current, which can be considered small in the respect of the stator voltage, the variation of stator flux can be ascribed all to the voltage applied. So, a proportional relationship between flux variation and voltage in a given cycle T_c can be found by discretizing (1).

$$\Delta\overrightarrow{\varphi_S} \cong T_c \cdot \overrightarrow{i_S} \qquad (2)$$

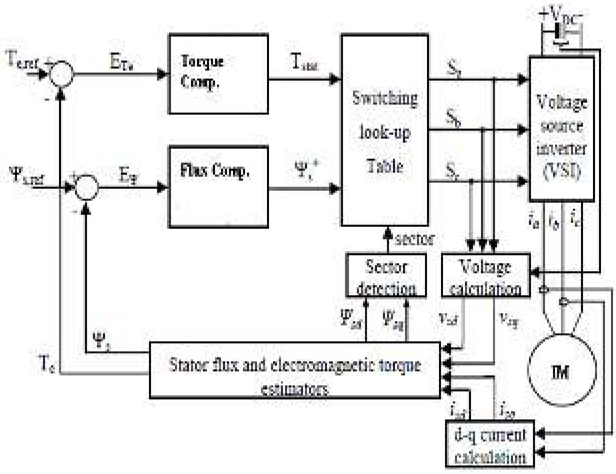

Figure 1. The conventional DTC scheme of IM drive system

Analyzing the equation binding the stator and rotor fluxes (φ_S and φ_r) to the torque (T_e), it is possible to find that an augmentation of the angle between fluxes (ϑ_{sr}) means an augmentation of torque, as (3) shows, where M, σ, L_S and p are the mutual inductance, the leakage inductance and number of poles respectively.

$$T_e = \frac{3}{2} \cdot \frac{p}{2} \cdot \frac{M}{\sigma \cdot L_S} \cdot \varphi_S \cdot \varphi_r \cdot \sin\vartheta_{sr} \qquad (3)$$

The relationship between stator and rotor fluxes it can be assumed that a fast variation of the stator flux angular speed will reflect in an increment of the angle ϑ_{sr} as Figure 2 schematically shows. So, imposing a particular stator voltage, it is possible to control either the stator flux amplitude or the torque. The vector $\Delta\overrightarrow{\varphi_S} \cong T_C \cdot \overrightarrow{U_S}$ can be decomposed in the component parallel and perpendicular to the stator flux; the parallel component modifies the stator flux amplitude while the perpendicular component controls the torque.

SVM techniques have several advantages such as, lower torque ripple, lower Total Harmonic Distortion (THD) in the AC motor current, lower switching losses, and easier to implement in the digital systems. At each cycle period, this SVM technique is used to obtain the voltage space vector required to exactly compensate the flux and torque errors. The torque ripple for this SVMDTC is significantly improved and switching frequency is maintained constant. SVM is based on the switching between two adjacent boundary active vectors and a zero space vector. Space vector modulation (SVM) is one of the preferred real-time modulation techniques and is widely used for digital control of voltage source inverters.

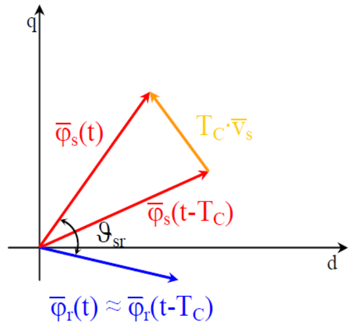

Figure 2. DTC Principles: vector representation of the stator and rotor fluxes during a sample interval T_C

A typical space vector diagram for the two-level inverter is shown in Figure 3, where the six active vectors V_1 to V_6 form a regular hexagon with six equal sectors (I to VI). The zero vector V_0 lies on the center of the hexagon.

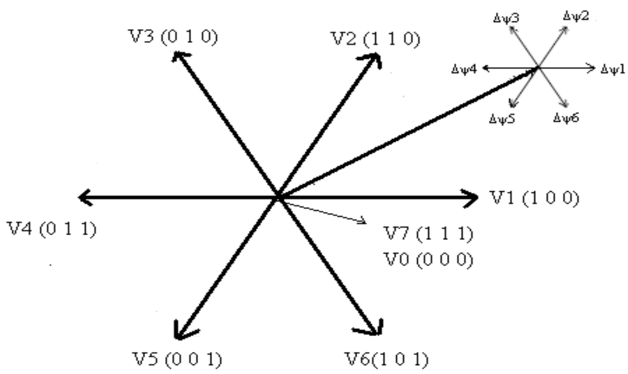

Figure 3. Inverter voltage vectors and corresponding stator flux variation

Table 1 summarizes the flux and torque change for applying the voltage vectors. The flux can be increased by the V_1, V_2, V_6 vectors, whereas it can be decreased by V_3, V_4, V_5 vectors. Similarly, torque is increased by the V_2, V_3, V_4 vectors, but decreased by the V_1, V_5, V_6 vectors. The zero vectors (V_0 or V_7) short-circuit the machine terminals and keep the flux and torque unaltered. Due to finite resistance drop, the torque and flux will slightly decreases during the short-circuit condition.

Table 1. Flux and torque variations due to applied voltage vector (Arrow indicates magnitude and direction)

Voltage Vector	V_1	V_2	V_3	V_4	V_5	V_6	V_7 (or) V_0
ψ_s	↑	↑	↓	↓	↓	↑	0
T_e	↓	↑	↑	↑	↓	↓	↓

The command stator flux and torque values are compared with the actual values in hysteresis flux and torque controllers, respectively. The flux controller is a 2-level while the torque controller is 3-level comparator. The digitized output signals of the flux (dψ) and torque (dm) controllers are as follows:

$d\psi = 1$ for $E\psi > +H\psi$
$d\psi = -1$ for $E\psi < -H\psi$
$dm = 1$, for $E_{Te} > +H_m$
$dm = -1$, for $E_{Te} < -H_m$
$dm = 0$, for $-H_m < E_{Te} < +H_m$

Where, $E\psi$ and E_{Te} are the flux and torque errors. And $H\psi$ and H_m are the acceptable predefined torque errors, respectively.

The digitized variables dψ, dm and stator flux sector S, obtained from the angular position $\gamma_s = \arctan(\lambda_{qs}/\lambda_{ds})$ .The stator input voltages are evaluated in order to determine the stator voltage vector. Having the control strategy (switching pattern), the stator voltage vector can be directly calculated as follows:

$$V_s = \sqrt{\frac{2}{3}} \cdot V \left(s_a + s_b \cdot e^{j\frac{2\Pi}{3}} + s_c \cdot e^{-j\frac{2\Pi}{3}} \right) \quad (4)$$

where V is the inverter supply voltage (DC link voltage), and s_a, s_b and s_c are numbers 0 or 1 that are the output of switching table. In Table 2, the three digit numbers define the switching algorithm where the digits from left to right give values of s_a, s_b and s_c, respectively.

Table 2. Voltage vector switching table

dΨ	*dm*	*S(1)*	*S(2)*	*S(3)*	*S(4)*	*S(5)*	*S(6)*
1	1	110	010	011	001	101	100
	0	000	111	000	111	000	111
	–1	101	100	110	010	011	001
–1	1	010	011	001	101	100	110
	0	111	000	111	000	111	000
	–1	001	101	100	110	010	011

3. Fuzzy Duty Ratio Controller DTC

Figure 4 shows a block diagram of the duty ratio-based DTC. In this control the selected inverter, switching state is applied for a portion of switching period and the zero switching state is applied for the rest of the period. During the zero switching state, the inverter applies zero voltage to the machine there by keeping the current and therefore the torque almost constant. The average input voltage to the motor during each switching state is then given by [13].

$$V = \delta \cdot V_{DC} \, . \quad (5)$$

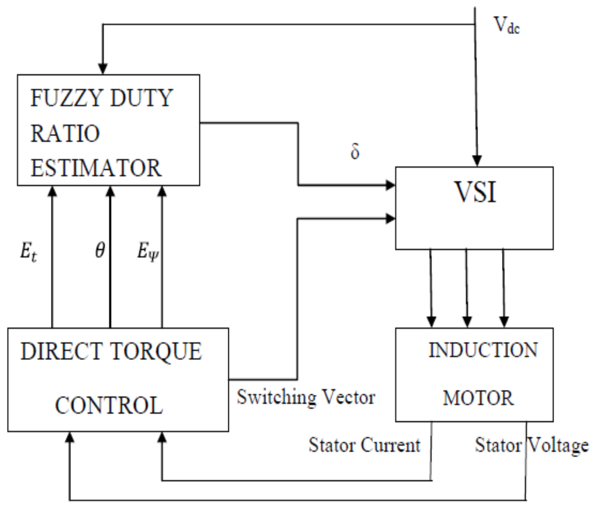

Figure 4. Block Diagram of Duty Ratio Controlled DTC

By varying δ between 0 and 1, any voltage between 0 and V_{DC} can be applied during each switching period, thus increasing the choice of the voltage vector which was limited by the number of switching states in conventional DTC. The duty ratio is chosen to give voltage vector whose average over the switching cycle gives the desired change in torque thereby reducing the torque ripple.

Fuzzy controller includes three inputs (torque error E_{te}, flux error E_λ, and the position of the stator flux linkage according to corresponding sector) and one output (duty ratio δ).The fuzzy logic controller is a Mamdani type and contains a rule base. This base comprises of two groups of rules, each of which contains nine rules. The first group is used when the stator flux linkage modulus is smaller than its reference value (Table 3), and the second group of rules is used when it is greater than its reference value (Table 3). There are together 18 simple rules and only three fuzzy sets.

The Membership Function for torque error, angle and duty ratio are shown in Figures 5, 6 and 7.

Table 3. Fuzzy Rules for Duty Ratio Control

S.No	Group 1 Rules	Group 2 Rules
1	If E_{te} is small and θ_S is small then δ is medium	If E_{te} is small and θ_S is small then δ is small
2	If E_{te} is small and θ_S is medium then δ is small	If E_{te} is small and θ_S is medium then δ is small
3	If E_{te} is small and θ_S is large then δ is small	If E_{te} is small and θ_S is then large δ is medium
4	If E_{te} is medium and θ_S is small then δ is medium	If E_{te} is medium and θ_S is small then δ is medium
5	If E_{te} is medium and θ_S is medium then δ is medium	If E_{te} is medium and θ_S is medium then δ is medium
6	If E_{te} is medium and θ_S is large then δ is medium	If E_{te} is medium and θ_S is large then δ is large
7	If E_{te} is large and θ_S is small then δ is large	If E_{te} is large and θ_S is small then δ is medium
8	If E_{te} is large and θ_S is medium then δ is large	If E_{te} is large and θ_S is medium then δ is large
9	If E_{te} is large and θ_S is large then δ is large	If E_{te} is large and θ_S is large then δ is large

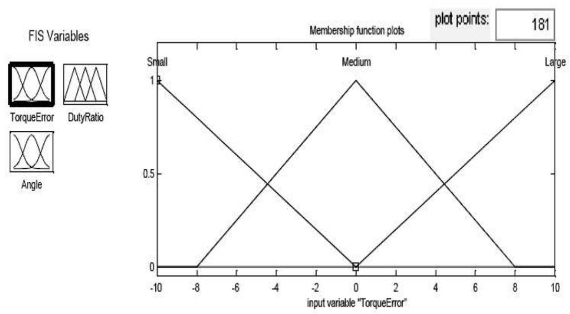

Figure 5. Membership function for Torque Error

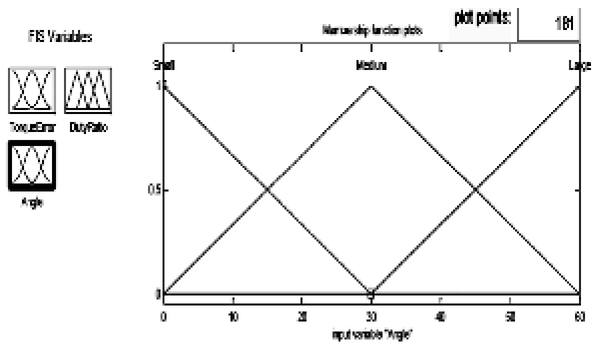

Figure 6. Membership function for Angle

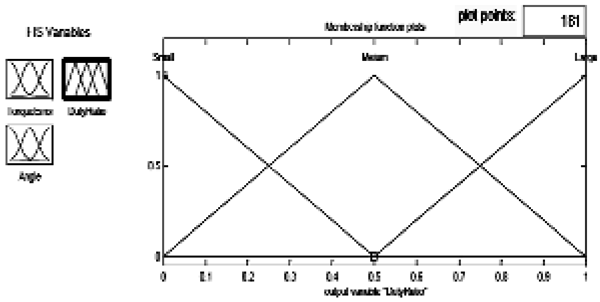

Figure 7. Membership function for Duty Ratio

4. Simulation Result and Discussions

In order to show the effectiveness of the control scheme a simulation has been carried out for an induction motor with the specification given in Appendix. The control scheme is simulated with, MATLAB/SIMULINK which is the most popular and powerful tool for simulation. The speed reference prescribed to (800; 1200) rpm at t = (0; 1.5) seconds. The load torque prescribed to (0; 10; 20) Nm at t = (0; 0.5; 1.5) seconds with step variation.

Figure 8(a) shows the speed torque responses of the induction motor at different conditions i.e. the constant speed command 800 rpm is given for 0 to 1.5 seconds and the load torque is changed at 0.5 second from 0 to 10 Nm. From 1 to 1.5 seconds the load torque is maintained at 10 Nm, but the speed command is changed at 1.5 second from 800 rpm to 1000 rpm. Also at 1.5 second the load torque is changed from 10 Nm to 20 Nm.

Figure 8(b) shows that if the speed command is changed suddenly then the induction motor produces a large electromagnetic torque, which is undesirable.

Figure 8(c) shows the stator flux linkage response of conventional DTC. Figure 8(d) shows the stator current response of conventional DTC.

Figure 8(e) shows that the torque ripple in case of conventional DTC is ± 5 Nm.

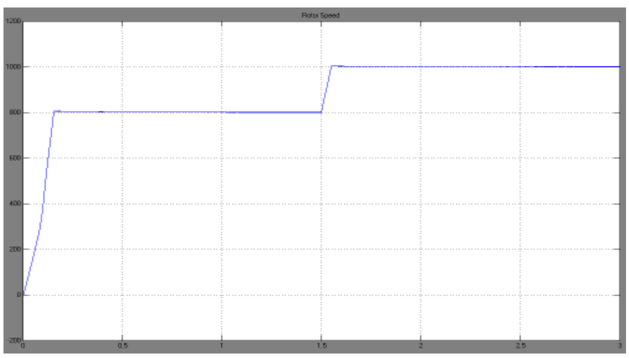

Figure 8(a). Rotor Speed [rpm] vs. Time [s] – conventional DTC

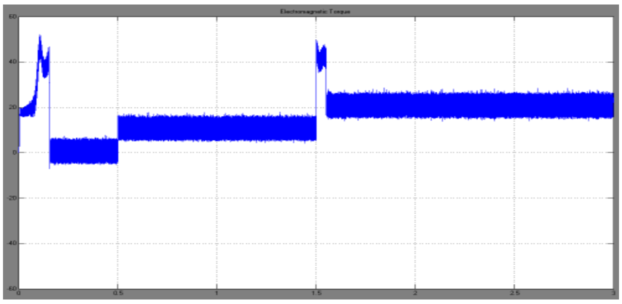

Figure 8(b). Electromagnetic Torque [Nm] vs. Time [s] – conventional DTC

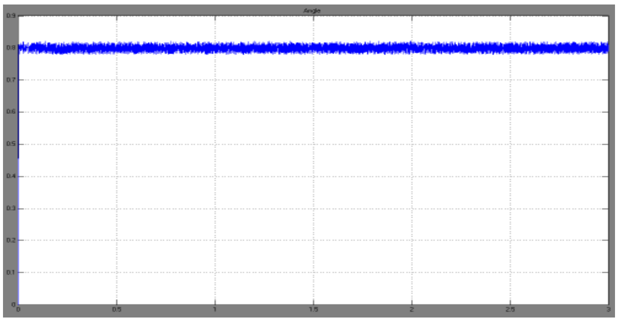

Figure 8(c). Stator Flux Linkage vs. Time – conventional DTC

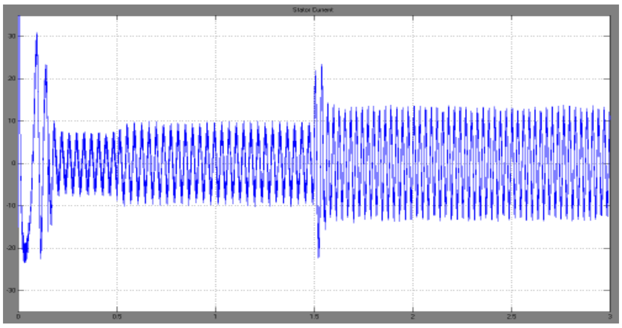

Figure 8(d). Stator Current (A) vs. Time (s) – conventional DTC

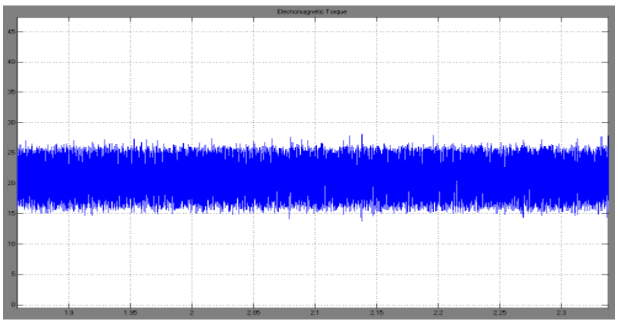

Figure 8(e). Torque Ripple in Conventional DTC

Figures 9 (a, b, c and d), shows that the speed, Electromagnetic Torque, Stator flux linkage and Stator Current responses of FLDRC DTC.

Figure 9(e) shows that the torque ripples in fuzzy logic duty ratio controlled DTC is ± 3 Nm which is very much less as compared to conventional DTC. As in duty ratio control technique, instead of applying a voltage vector for the entire switching period, it is applied for a portion of the switching period and the zero switching state is applied for the rest of the period the ripples is considerably reduced. Based on the simulation results the following conclusions are considered.

FLDRC-DTC system provides fast torque response and better speed accuracy than the conventional DTC strategy. Steady State torque ripple is considerably reduced.

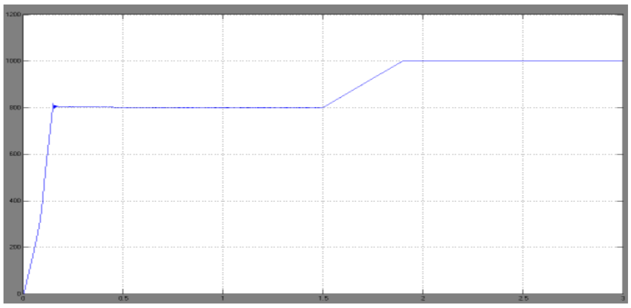

Figure 9(a). Rotor Speed (rpm) vs. Time(s) – FLDRC DTC

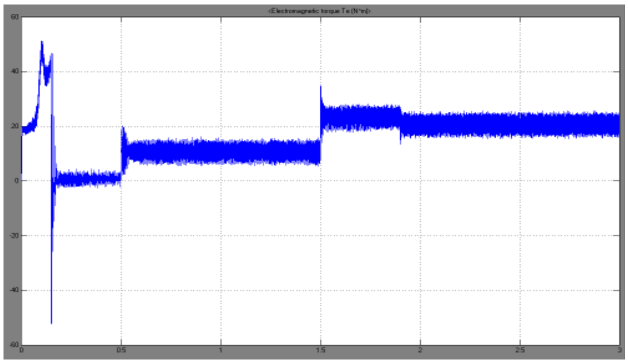

Figure 9(b). Electromagnetic Torque (N-M) vs. Time (s) – FLDRC DTC

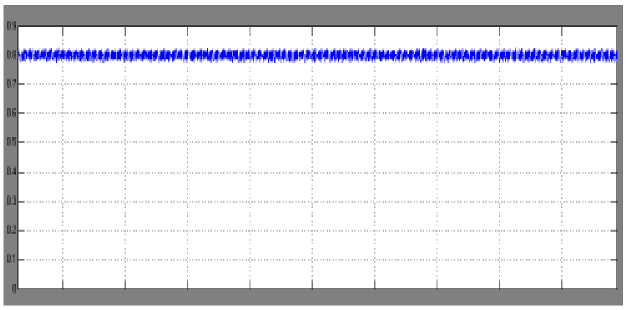

Figure 9(c). Stator Flux Linkage vs. Time (s) – FLDRC DTC

The SVM direct torque control strategy provides fast torque response and better speed accuracy than both conventional DTC and duty ratio control technique. Steady State torque ripple is considerably reduced. The torque ripple in this technique is very less compared to both conventional and duty ratio control DTC.

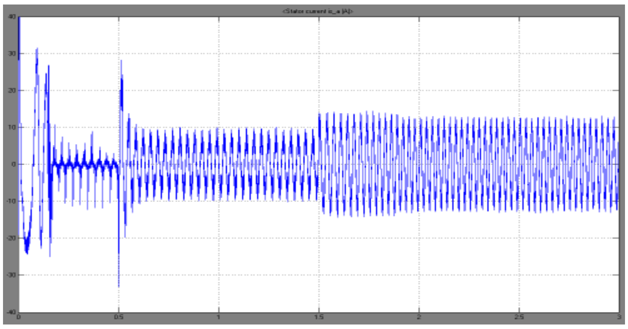

Figure 9(d). Stator Current (A) vs. Time (s) – FLDRC DTC

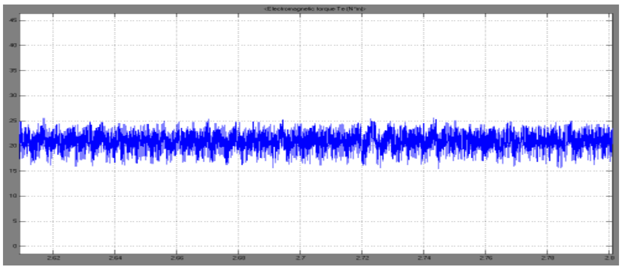

Figure 9(e). Torque Ripple in DTC using Duty Ratio Control Technique

Figures 10 (a, b, c and d) shows that the speed, Electromagnetic Torque, Stator flux linkage and Stator Current responses of SVM – DTC.

Figure 10(e) shows that the torque ripple present in DTC-SVM is ± 1, which is much less as compared to conventional DTC (± 5) and duty ratio controlled DTC (± 3). Also the flux ripple is reduced considerably in this case.

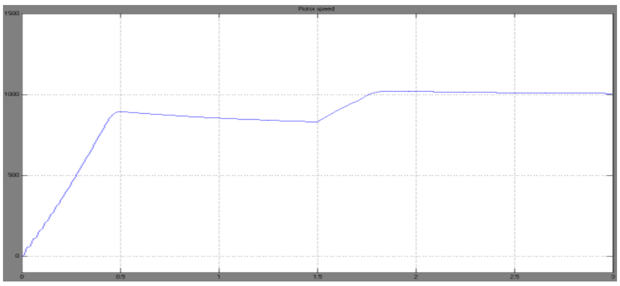

Figure 10(a). Speed (rpm) vs. Time (s) – SVM DTC

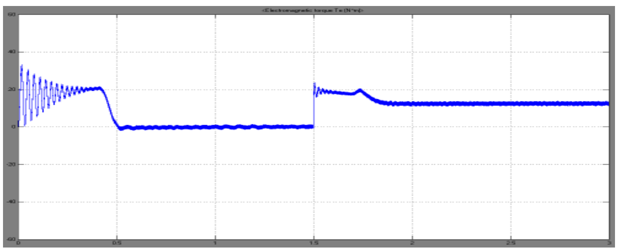

Figure 10(b). Torque (Nm) vs. Time (s) – SVM DTC

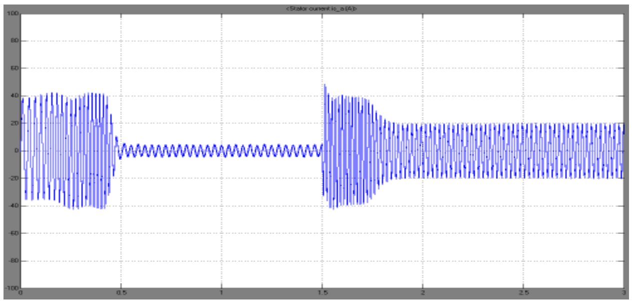

Figure 10(c). Stator Current (A) vs. Time(s) – SVM DTC

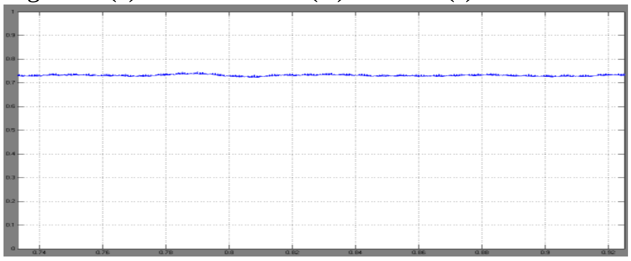

Figure 10(d). Stator Flux Linkage vs. Time(s) – SVM DTC

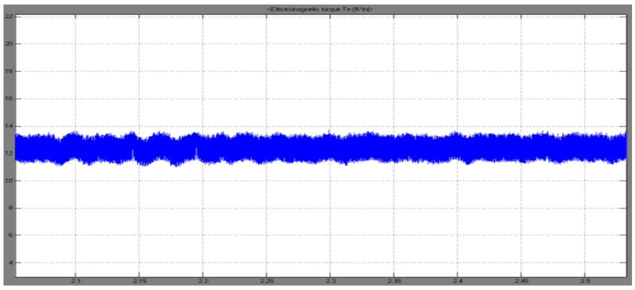

Figure 10(e). Torque Ripple in DTC-SVM

5. Conclusion

This work presents a comparative study of different direct torque control strategies of induction motor drive based on their simulation results. Two direct torque control strategies (duty ratio control and space vector modulation) are compared with the conventional direct torque control scheme. A comparative analysis among the conventional direct torque control, duty ratio control and space vector modulation, strategies are made by simulation in MATLAB/SIMULINK. Based on simulation results, it can be seen that the ripple in torque with duty ratio control is less than the one with conventional DTC. The effects of the duty ratio controller on the stator flux and current are also presented. As seen there are improvements in the waveforms of duty ratio control compared to the conventional DTC.

Appendix

Power Rating: 10 HP
Stator Voltage: 460 Volt
Frequency: 60 Hz

Number of Poles: 4
Stator Resistance: 0.6837 Ohm/phase
Stator leakage Inductance: 0.004152 H/phase
Rotor Resistance: 0.451 Ohm/phase
Rotor leakage Inductance: 0.004152 H/phase
Mutual Inductance: 0.1486 H
Inertia: 0.05 kg·m^2
Friction Coefficient: 0.0081412

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Received in January 2013
(and revised form in February 2013)