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Direct Torque Control Technique for Voltage Source Inverter Fed Induction Motor Drive

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Abstract

The aim of this paper is to develop an efficient and simple algorithm known as Direct Torque Control (DTC) based on Space Vector Modulation (SVM) technique applicable for induction motor drives. The motor is supplied with voltage source inverter. The inverter reference voltage is obtained by selecting appropriate voltage vector from SVM based switching table. The proposed SVM based DTC can reduce torque ripples and preserve DTC transient merits such as fast torque response in wide speed range. To validate the proposed method simulation has been carried out using MATLAB – SIMULINK. Simulated results presented in this paper prove low torque ripple and fast torque response. The simulation results verify the superiority of the proposed technique to the conventional DTC technique.

Keywords: Direct torque control, Induction motor drive, Space vector modulation, Switching table.

Introduction

In early days dc machine played an important role in variable speed drives applications since the magnetic flux and torque can be easily controlled independently by the stator and rotor currents respectively [1]. After that the advancement on power semiconductor devices made ac machines to become popular in variable speed drives [2]. The introduction of field oriented control (FOC) in 1970s made huge turn in the control of induction motor (IM) drive. FOC uses frame transformation to decouple the torque and flux components of the stator current. Therefore the performance of IM becomes similar to that of the dc motor. The implementation of this system however is complicated and is well known to be highly sensitive to parameter variations due to the feed forward structure of its control system [3]. Later in the eighties a new control technique named Direct Torque Control (DTC) is introduced [4], [5]. The DTC is characterized by its simple structure and fast dynamic response. As the inverter is directly controlled by the algorithm, no modulation technique is needed. The main advantages of DTC are absence of co-ordinate transformation and current regulator, absence of separate voltage modulation block [6]. Common disadvantages of conventional DTC are sluggish response in both starts up and load changes and torque ripples [7]. Recent advancements in DTC systems include the use of unified flux control scheme [8], space vector modulation (SVM) technique [9], stator flux vector control in field weakening region [10], torque ripple minimization techniques [11], SVM with adoptive stator flux observer [12], fuzzy logic [13], neuro - fuzzy [14], FPGA [15]. In the proposed technique SVM is used to obtain the reference voltage space vector to exactly compensate the flux and torque errors. The torque ripples of SVM based DTC can be significantly reduced.

This paper is organized as follows. Section II presents the induction motor model in d-q axes. Section III presents SVM based DTC algorithm. Section IV presents the simulation results of the proposed method. Finally this paper is concluded in section V.

Induction Motor Model

Under assumption of linearity of the magnetic circuit neglecting iron loss, a mathematical model of three phase IM in a stationary d-q axes is expressed by (1),

$$\frac{d}{dt}\begin{pmatrix} i_{qs}{}^{s} \\ i_{ds}{}^{s} \\ i_{qr}{}^{s} \\ i_{dr}{}^{s} \end{pmatrix} = \frac{1}{\sigma L_s L_r}\left\{\begin{pmatrix} -R_s L_r & -\omega_r L_m{}^2 & R_r L_m & -\omega_r L_r L_m \\ \omega_r L_m{}^2 & -R_s L_r & \omega_r L_r L_m & R_r L_m \\ R_s L_m & \omega_r L_s L_m & -R_r L_s & \omega_r L_s L_r \\ -\omega_r L_s L_m & R_s L_m & -\omega_r L_s L_m & -R_r L_s \end{pmatrix}\begin{pmatrix} i_{qs}{}^{s} \\ i_{ds}{}^{s} \\ i_{qr}{}^{s} \\ i_{dr}{}^{s} \end{pmatrix} + \begin{pmatrix} L_r & 0 & -L_m & 0 \\ 0 & L_r & 0 & -L_m \\ -L_m & 0 & L_s & 0 \\ 0 & -L_m & 0 & L_s \end{pmatrix}\begin{pmatrix} v_{qs}{}^{s} \\ v_{ds}{}^{s} \\ v_{qr}{}^{s} \\ v_{dr}{}^{s} \end{pmatrix}\right\} \qquad (1)$$

Here σ = 1- (Lm2 / LsLr)

where vd, vq, id, iq are the voltage and stator current vector components in d-q axes, ωr is the rotor electrical angular speed, Ls, Lr, Lm are the stator, rotor and magnetizing inductances, respectively, and Rs, Rr are the stator and rotor resistances, respectively [2].

Principles of DTC

The basic principle of DTC is the direct selection of a space vector and corresponding control signals in order to regulate instantaneously the electromagnetic torque and stator flux magnitude. DTC provides very quick response with simple control structure and hence this technique is gaining popularity in industries [16], [17]. In DTC, stator flux and torque are directly controlled by selecting the appropriate inverter state. The stator currents and voltages are indirectly controlled hence no current feedback loops are required. Nearly sinusoidal stator fluxes and stator currents enable high dynamic performance even at standstill [18].

The generic DTC scheme for a Voltage source PWM inverter-fed IM drive is shown in Fig.1. The scheme includes two hysteresis controllers. The stator flux controller imposes the time duration of the active voltage vectors, which move the stator flux along the reference trajectory, and the torque controller determinates the time duration of the zero voltage vectors which keep the motor torque in the predefined hysteresis tolerance band. At every sampling time the voltage vector selection block chooses the inverter switching state (SA, SB, SC) which reduces the instantaneous flux and torque errors.

Basic Switching Table and Selection of Voltage Vectors based on Space Vector Modulation

The basic idea of the switching table DTC concept is shown in Fig. 1. The command stator flux Ψsref, and torque Teref values are compared with the actual Ψs and Te values in hysteresis flux and torque controllers, respectively. The flux controller is a two-level comparator while the torque controller is a three level comparator. The digitized output signals of the flux controller are defined as in (2) and (3)

$$\psi_{serr} = 1, \; for \; \psi_s < \psi_{sref} - H_\psi \qquad (2)$$

$$\psi_{serr} = -1, \; for \; \psi_s < \psi_{sref} + H_\psi \qquad (3)$$

And those of the torque controller are as in (4), (5), (6),

$$T_{eerr} = 1, \; for T_e < T_{eref} - H_m \qquad (4)$$

$$T_{eerr} = 0, \; for T_e = T_{eref} \qquad (5)$$

$$T_{eerr} = -1, \; for T_e < T_{eref} + H_m \qquad (6)$$

Where 2HΨ is the flux tolerance band and 2Hm is the torque tolerance band.

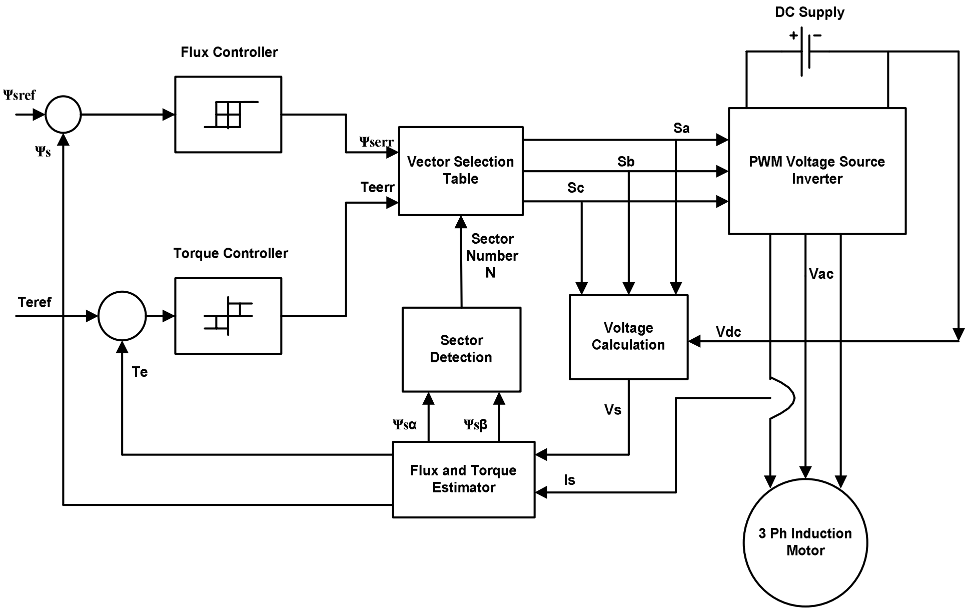

Figure 1: Basic scheme of PWM inverter fed induction motor with DTC.

The digitized variables Ψserr, Teerr and the stator flux section (sector) N obtained from the angular position

$$\alpha = \mathrm{arctg}\ (\Psi s\beta / \Psi s\alpha) \tag{7}$$

create a digital word which is used to select the appropriate voltage vector. The stator voltage space vector Vs is calculated using the dc link voltage Vdc and the gating signals Sa, Sb, Sc as given in (8)

$$\overline{V_s}^{s} = \frac{2V_{dc}}{3}\left(S_a + e^{j2\Pi/3} S_b + e^{j4\Pi/3} S_c \right) \tag{8}$$

On the basis of torque and flux hysteresis status and the position of stator flux switching sector, which is denoted by α, SVM selects the inverter voltage vector from the Table1. The outputs of the switching table are the settings for the switching devices of the inverter. Fig.2 shows the relation of inverter voltage vector and stator flux switching sectors. Six active switching vectors V1, V2, V3, V4, V5, V6 and two zero switching vectors V0 and V7 determine the switching sequence of the inverter. Depending on inverter switching pulses, PWM is achieved and hence stator voltages and currents are controlled [19]. Therefore to obtain a good dynamic performance, an appropriate inverter voltage vectors Vi (i=1 to 6) has to be selected.

Stator Flux Control

By selecting the appropriate inverter output voltage Vi (i=1-6), the stator flux Ψs rotates at the desired frequency ωs inside a specified band. If the stator ohmic drops are neglected, the stator voltage is directly proportional to the stator flux in accordance with (9) and (10).

$$\overline{V}_s = \frac{d\overline{\psi}_s}{dt} \tag{9}$$

$$d\overline{\psi}_s = \overline{V}_s dt \tag{10}$$

Therefore the variation of the stator flux space vector due to the application of the stator voltage vector $\overline{V}$ s during a time interval of Δt can be approximated as in equation (11).

$$\Delta\overline{\psi}_s = \overline{V}_s \Delta t \tag{11}$$

Torque Control

$$T_e = \frac{3}{2}\frac{p}{2}\frac{L_m}{L_r L_s^{'}}\psi_s \psi_r \sin\gamma \tag{12}$$

The electromagnetic torque given by equation (12) is a sinusoidal function of γ, the angle between Ψs and Ψr as shown in Fig.3.

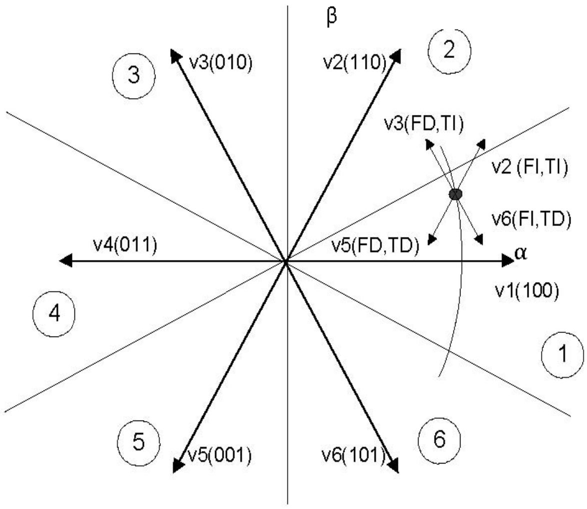

Figure 1: Inverter voltage vectors and stator flux

The variation of stator flux vector will produce a variation in the developed torque because of the variation of the angle γ between the two vectors as in equation (13).

$$\Delta T_e = \frac{3}{2}\frac{p}{2}\frac{L_m}{L_r L_s'}(\psi_s + \Delta\psi_s)\Psi_r \sin\Delta\gamma \tag{13}$$

Where Ls’ = LsLr – Lm2

In accordance with the Fig. 1, the flux linkage and torque errors are restricted within its respective hysteresis bands. It can be proved that the flux hysteresis band affects the stator-current distortion in terms of low order harmonics and the torque hysteresis band affects the switching frequency.

The DTC requires the flux and torque estimations, which can be performed as proposed in this model, by means of two different phase currents and the state of the inverter. The flux and torque estimations can be performed by means of other estimators using other magnitudes such as two stator currents and the mechanical speed, or two stator currents again and the shaft position [19].

Stator Flux Estimator

In the stationary reference frame, the d and q axes stator fluxes are estimated based on (14), (15).

$$\overline{\psi}_{ds} = \int \left(\overline{V}_{ds} - \overline{i}_{ds} R_s\right) dt \tag{14}$$

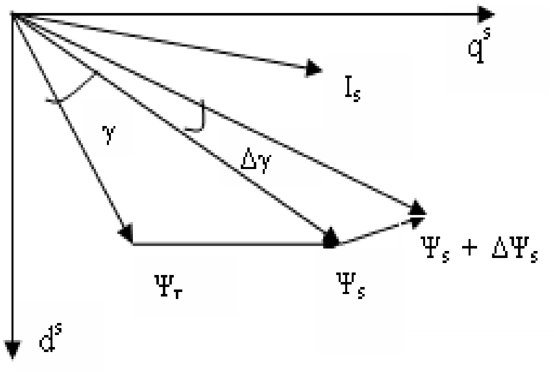

Figure 2: Stator flux and rotor flux space vectors.

$$\overline{\psi}_{qs} = \int \left(\overline{V}_{qs} - \overline{i}_{qs} R_s\right) dt \tag{15}$$

$$\overline{\psi}_{s} = \sqrt{\overline{\psi}_{ds}^{\,2} + \overline{\psi}_{qs}^{\,2}} \tag{16}$$

Electromagnetic Torque Estimation

From the estimated stator flux and current components the electromagnetic torque of the motor is calculated as in (17)

$$T_e = 3\,\frac{p}{2}\left(\overline{\psi}_{ds}\,\overline{i}_{qs} - \overline{\psi}_{qs}\,\overline{i}_{ds}\right) \tag{17}$$

Table 1: Switching table of Inverter Voltage Vectors

Ψserr	Teerr	α(1) sect1	α(2) sect 2	α(3) sect3	α(4) sect4	α(5) sect5	α(6) sect 6
1	1	V2	V3	V4	V5	V6	V1
	0	V7	V0	V7	V0	V7	V0
	-1	V6	V1	V2	V3	V4	V5
0	1	V3	V4	V5	V6	V1	V2
	0	V0	V7	V0	V7	V0	V7
	-1	V5	V6	V1	V2	V3	V4

Simulation Results

MATLAB/SIMULINK is a software package for modeling, simulating and analyzing dynamic systems [11]. Fig. 4 illustrates the complete model of DTC drive, which consists of an induction machine, stator flux and torque estimators, torque and flux controllers, voltage source inverter (VSI).

The induction machine model used for simulation is constructed using sub system with M-file based on stationary reference frame model in d-q axes which is shown in fig. 5. The induction machine parameters used for simulation are given in table II.

The magnitude and phase angle of stator flux are calculated using SIMULINK model based on equations (15) and (16) as shown in fig. 6.

The Cartesian to polar block converts d-q axes stator flux into its magnitude and phase angle. The SIMULINK model is used for torque estimation based on equation (17). Stator flux and torque controllers are constructed based on S-function. Voltage vector selection table is simulated using S- function. The torque and flux error states and the flux position become the inputs of the selection table. Consequently it outputs the switching pattern of the three phase VSI as in fig.7.

Simulation was carried out and the significance of DTC and SVM are proved. Simulation results of inverter output voltage, stator current,stator flux and electromagnetic torque are shown in fig.8, fig.9, fig.10 and fig.11 respectively.

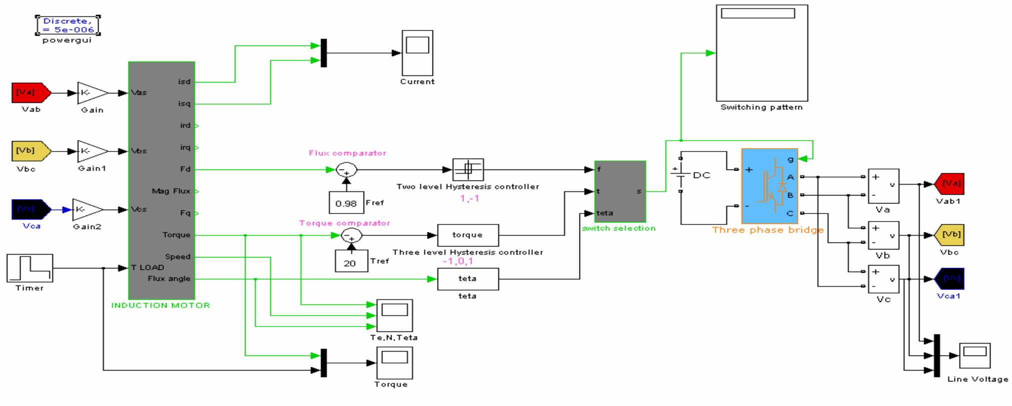

Figure 4: Simulink Model of Space Vector Modulation based Direct Torque Control

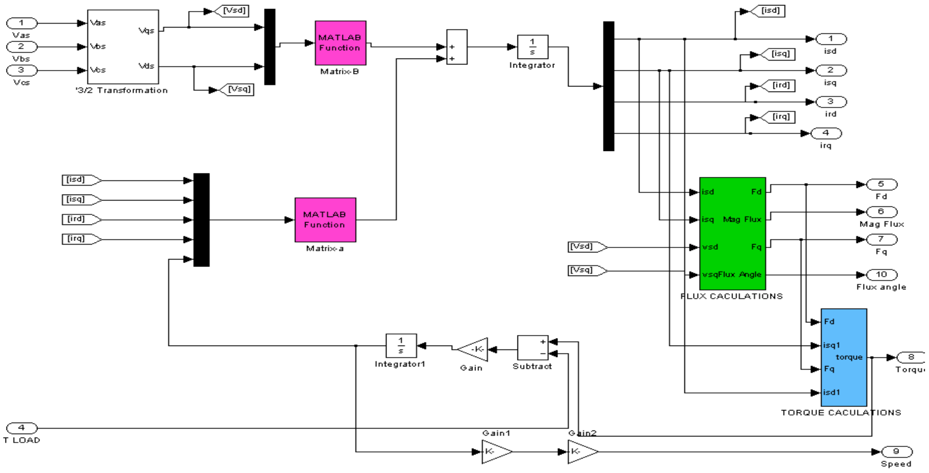

Figure 5: Simulink Model of Induction Machine

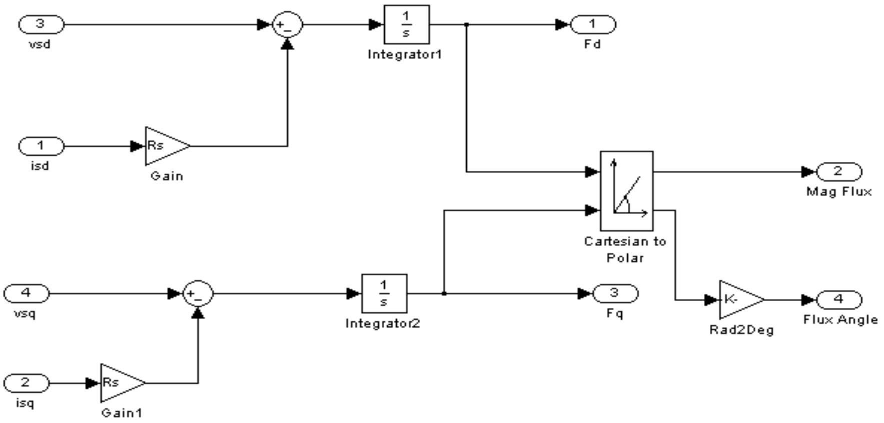

Figure 6: Simulink Model for magnitude and phase angle calculation of Stator Flux

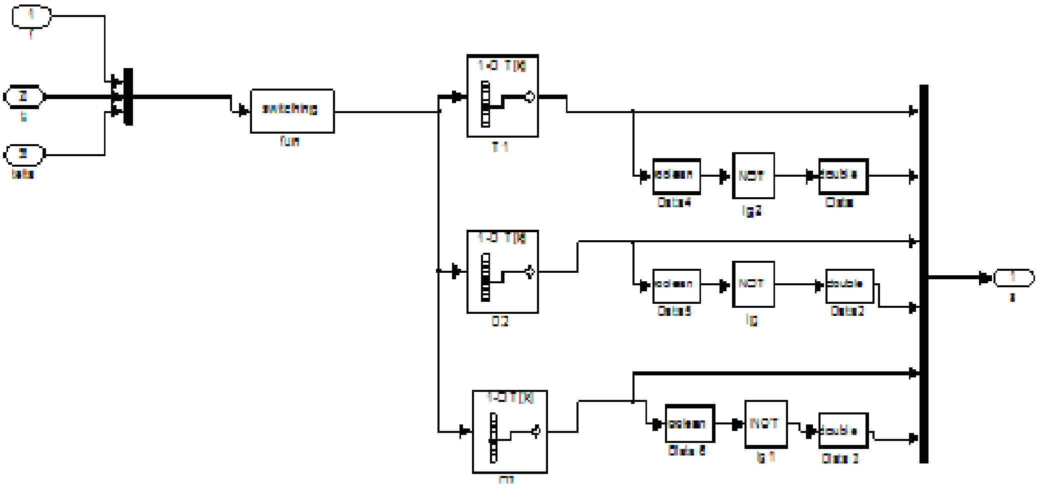

Figure 7: Simulink Model for Switching Pattern

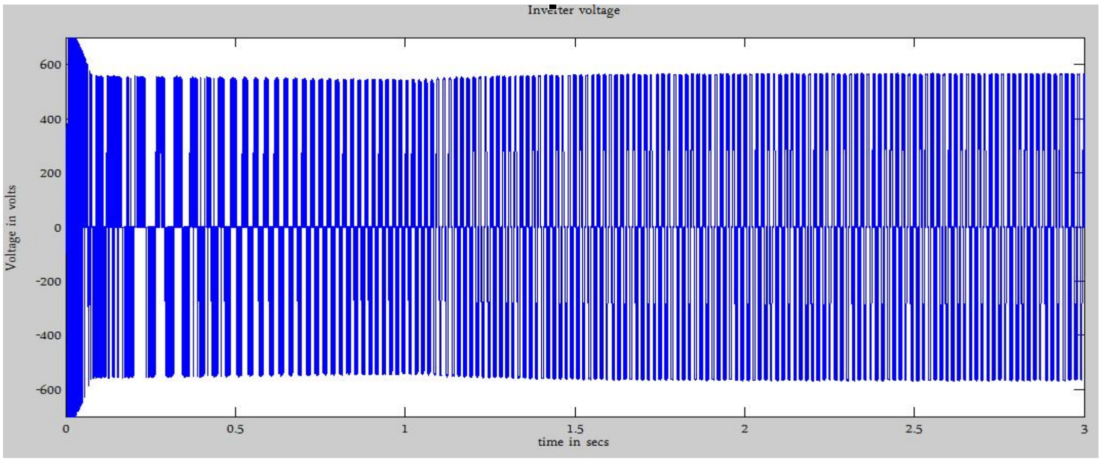

Figure 8: Simulation results of inverter output voltage

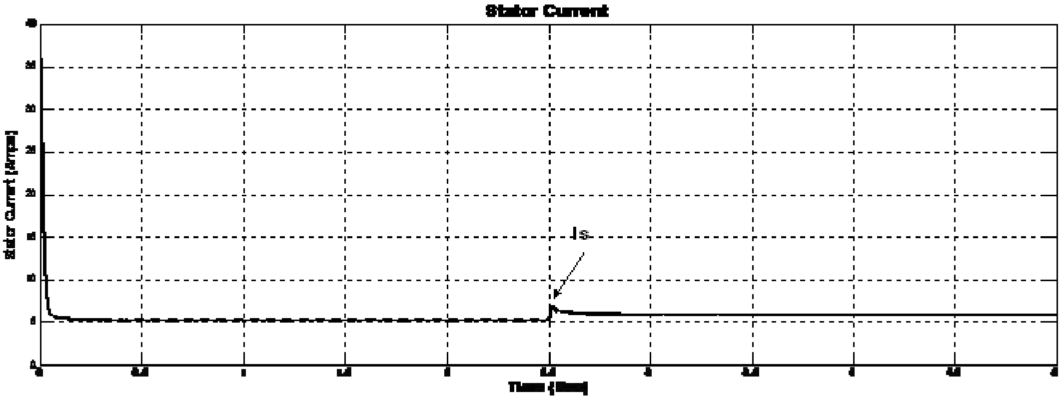

Figure 9 (a): Simulation results of Stator current

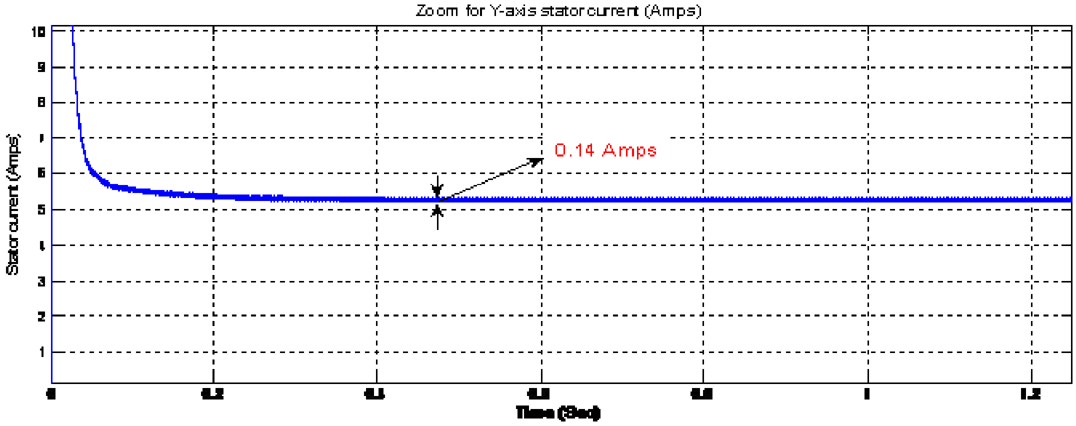

Figure 9 (b): Stator current zoom in Y axis

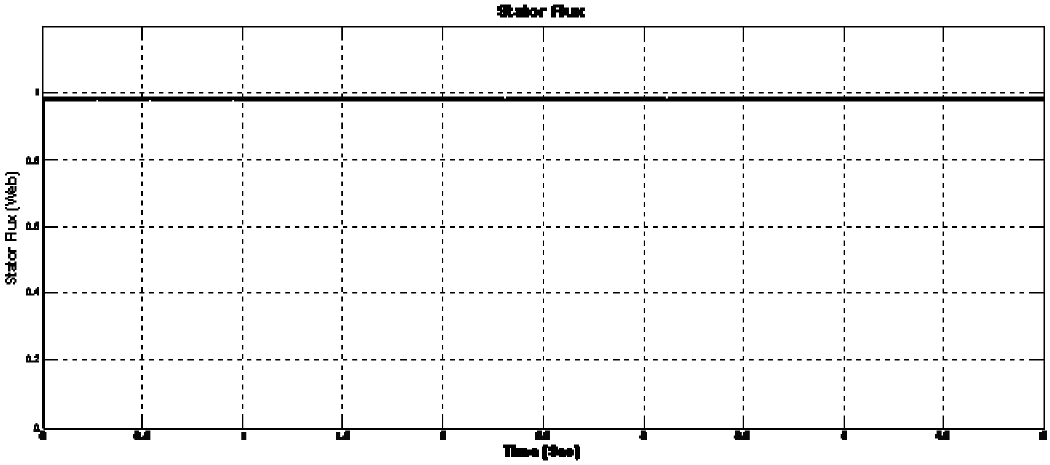

Figure 10 (a): Simulation results of Stator flux

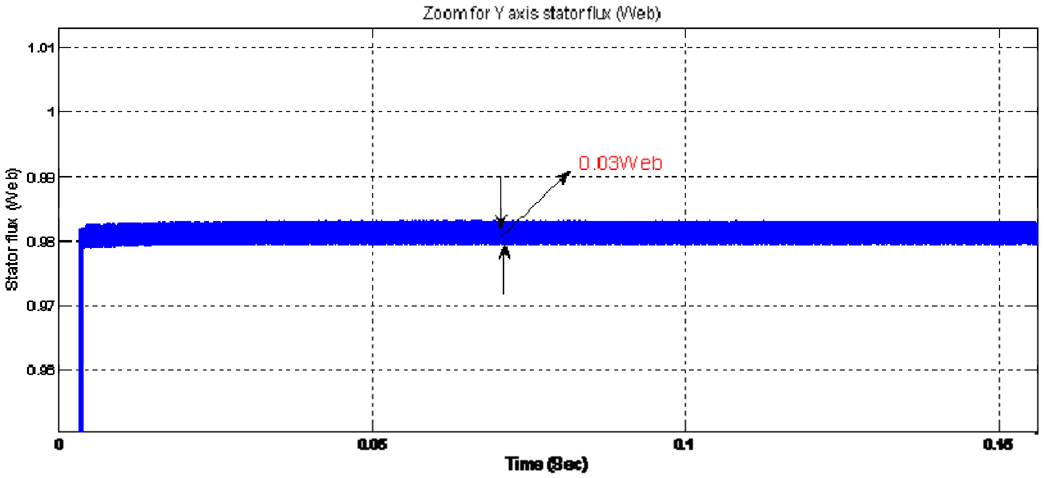

Figure 10 (b): Stator flux zoom in y axis

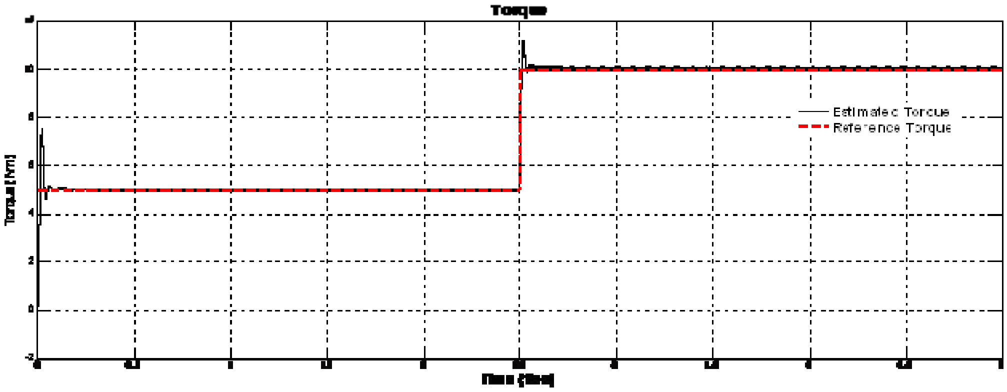

Figure 11 (a): Simulation results of Electromagnetic Torque

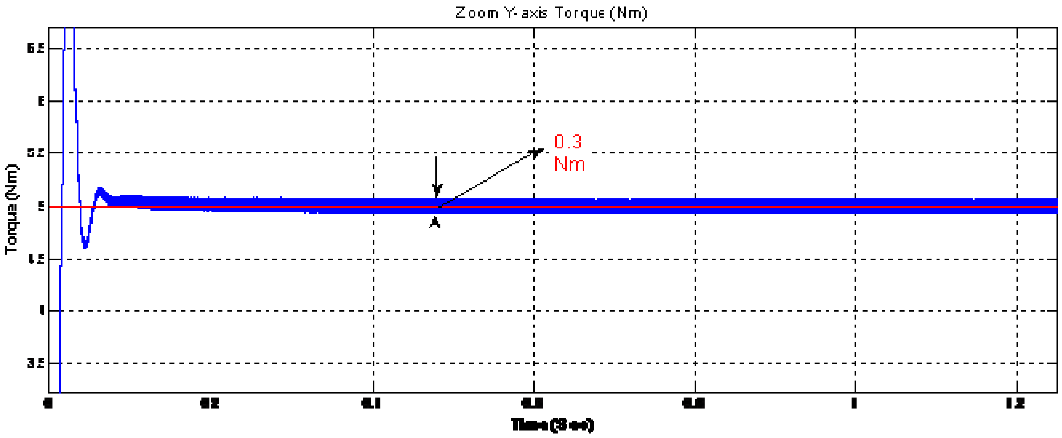

Figure 11 (b): Electromagnetic Torque zoom in y axis

Table 2: Induction machine parameters

Parameter	Symbol	Value
Stator resistance	Rs	1.85 Ω
Rotor resistance	Rr	1.84 Ω
Stator self inductance	Ls	170 mH
Rotor self inductance	Lr	170 mH
Mutual inductance	Lm	160 mH
Nominal Speed	ωr	1440 rpm
Nominal Voltage	Vs	380 V
No of pole pairs	p	2

Conclusion

The work carried out in this paper is aimed and focused to develop a Simulink model of SVM based DTC for induction motor drive. The DTC technique allows the independent and decoupled control of torque and stator flux. In order to show the effectiveness of the model, a numerical simulation has been carried out on a 3 kW induction machine fed by a voltage source inverter. The feasibility and validity of the developed DTC model, based on SVM and switching table technique, have been proved by simulation results obtained in the torque control mode. The main improvements shown are:

- Reduction of torque and current ripples in transient and steady state response.
- Smooth and fast torque response in transient state.

References

[1] Finch, J.W., and Giaouris, D.,2008, “Controlled AC Electrical drives”, IEEE Trans. on Industrial Electronics, 55, pp.481-491.

[2] Bose, B.K., 2001, Modern Power Electronics and AC Drives, Englewood Cliffs, NJ: Prentice-Hall.

[3] Krishnan, R., 2002, Electric Motor Drives- Modeling, Analysis, and Control, Prentice-Hall of India.

[4] Takahashi, L., and Noguchi, T., 1986, “A new quick response and high efficiency control strategy of an induction motor”, IEEE Trans. on Industry Applications, 1A-22, pp. 820-827.

[5] Takahashi, I., and Ohmori, Y., 1989, “High-performance direct torque control of an induction motor”, IEEE Trans. Ind. Applications, 25, pp. 257–264.

[6] Buja, G., Casadei, D., and Serra, G., 1997 “DTC- Based strategies for induction motor drives”, IEEE Proc. IECON’97.

[7] Abdul Wahab, H.F., and Sanusi, H., 2008, “Simullink Model of Direct Torque Control of Induction Machine,” American J. of Applied Sciences, 5, pp. 1083-1090.

[8] Ryu, J.H., Lee, K.W., and Lee, J.S., 2006, "A unified flux and torque control method for DTC based induction motor drives", IEEE Trans. on Power Electronics, 21, pp. 234-242.

[9] Buja, G.S., and Kazmierkowski, M.P., 2004, "Direct Torque control of PWM Inverter-Fed AC Motors — A Survey", IEEE Trans. on Industrial Electronics, 51, pp. 744–757.

[10] Mengoni, M., Zarri, L., Tani, M., Serra, G., and Casadei, D., 2008, "Stator flux vector control of Induction Motor drive in the field weakening region", IEEE Trans. on Power Electronics, 23,pp. 941-949.

[11] Idris, N.R.N., and Yatim, A.H.M., 2004, "Direct Torque control of Induction machines with constant switching frequency and reduced torque ripple", IEEE Trans. on Industrial Electronics, 51, pp. 758–767.

[12] Zhifeng, Z., Renyuan, T., Baodong, B., and Dexin, X., 2010, "Novel Direct Torque Control Based on Space Vector Modulation with Adaptive Stator Flux Observer for Induction Motors", IEEE Trans. on Magnetics, 46, pp. 3133-3137.

[13] Srinivasa Kishore Babu, Y., and Tulasi Ram Das, G., 2010, " Improvement in Direct Torque Control of Induction Motor using fuzzy logic duty ratio controller", ARPN J. of Engineering and Applied Sciences, 5(4), pp. 68-73.

[14] Habetler, T.G., Profumo, F., Astorelli, M., and Tolbert, L.M. , 1992, "Direct Torque control of induction motor using space vector modulation," IEEE Trans. on Industry Applications, 28, pp. 1045-1053.

[15] Sahoo, S.K., Das, G.K.R., and Subrahmanyam, V., 2008, "VLSI design approach to high - performance direct torque control of induction motor drives," World J. of Modelling and Simulation, England, 4, pp.269-276.

[16] www.abb.fi/vsd/index.htm

[17] Kazmierkowski, M.P., and Kasprowicz, A., 1995, "Improved direct torque and flux vector control of PWM inverter-fed induction motor drives," IEEE Trans. on Industrial Electronics, 42, pp. 344–350.

[18] Grabowski, P.Z., Kazmierkowski, M.P., Bose, B.K., and Blaabjerg, F., 2000, "A simple Direct Torque and Neuro – Fuzzy control of PWM inverter fed induction motor drive," IEEE Trans. on Industrial Electronics, 47, pp. 863-870.

[19] www.mathworks.com