S. Allirani[1],
V. Jagannathan[2]

J. Electrical Systems 9-3 (2013): 355-366

Regular paper

Modeling and Simulation of High performance Direct Torque Controlled Induction Motor Drive

JES
Journal of Electrical Systems

Abstract : This paper presents modeling and simulation of Field Programmable Gate Array (FPGA) based Direct Torque Control (DTC) of Induction Motor Drive fed by Space Vector Modulation (SVM) based Voltage Source Inverter (VSI) which allows precise and quick control of induction motor without calling for complex control algorithms. Also this technique is found to yield low steady state torque ripples and current distortions. At the same time the technique retains fast transient response, associated with DTC. FPGA is chosen due to its fast proto typing, simple hardware and software design and provides reduction in execution time.
Keywords : Direct Torque Control (DTC), Space Vector Modulation (SVM), Field Programmable Gate Array (FPGA), Induction Motor (IM).

1. INTRODUCTION

The induction motor is well known as the work horse of industry. It is estimated that induction motors are used in seventy to eighty percent of all industrial drive applications due to their simple mechanical construction, reliability, ruggedness, low cost and low maintenance requirement compared to other types of motors. Also it operates at essentially constant speed. These advantages are however suppressed from control point of view. When using an induction motor in industrial drives with high performance demands, the induction motors are non linear high order systems of considerable complexity [1]. The advancement of power electronics had made it possible to vary the frequency of the voltage or current relatively easy using various control techniques and thus has extended the use of induction motor in variable speed drive applications [2], [3].

Almost three decades ago, in [4] author presented the first control theory named Field Oriented Control (FOC) which was implemented after 10 years with microprocessors. Thirteen years later, a new control technique named direct torque control was developed and presented by [5], [6], [7] and [8]. The DTC control scheme is very simple compared to FOC. Conventional DTC consists of hysteresis controllers, flux and torque estimators and voltage source inverter. The advantages of DTC are

- Absence of frame transformation
- No current control loop, hence the current is not controlled directly
- It does not need pulse width modulator and position encoder which introduces delay and requires mechanical transducers.

In many variable speed drive applications, torque control is required where in closed loop speed control is not essential. An example of an application where torque is to be

[*] Corresponding author: S.Allirani,
[1] Associate Professor, Department of Electrical and Electronics Engineering, Sri Ramakrishna Engineering College, Coimbatore, Tamilnadu, India.
[2] Professor and Head (Rtd.), Department of Electrical and Electronics Engineering, Coimbatore Institute of Technology, Coimbatore, Tamilnadu, India.

controlled without precise speed control is traction drives for electric vehicles. Recently many research papers have been published in the area of DTC [9] - [17]. This DTC technique was implemented using digital signal processor. Then this algorithm was implemented using ASIC (Application Specific Integrated Circuit) design [18]. This paper focused on DTC in speed control mode in which the PI controller was implemented using VHDL (Very high speed Hardware Description Language) and presented the results. Papers [19], [20] presented a comparative analysis for DSP and FPGA based DTC. It was presented that the FPGA got better performance and precise in executing frequency. DTC was simulated using MATLAB and ModelSim simultaneously allowing a global co-simulation of the motor dynamics [21]. The author demonstrated the flexibility of the simulation tools. In [22], the author presented a simple torque controller instead of hysteresis comparators in order to maintain a constant switching frequency, and proposed a simple compensator to compensate the error associated in stator flux estimation based on voltage model. In [23], author presented a new torque and flux controllers and DTC was implemented using DSP and FPGA. The developed controllers reduced the torque and stator flux ripples and maintained a constant switching frequency.

In this paper the application of FPGA to SVM based direct torque control of induction motor drive is presented and simulation results are presented. The proposed model is simulated using Matlab and ModelSim 6.3.

The paper is organized as follows. Section II described the modeling of induction motor, Section III deals with SVM based DTC and section IV presented the simulation results and section V presented conclusion.

2. MODELLING OF THE INDUCTION MOTOR

2.1 Electrical Model

The mathematical model of the induction machine can be represented by a set of differential equations in the twin –axis (d-q) stationary reference frame.

$$\dot{i}_{ds} = (R_r L_r i_{ds} - \omega_r L^2_m i_{qs} - R_r L_m i_{dr} - \omega_r L_r L_m i_{qr} - L_r v_{ds}) / a_0$$
$$\dot{i}_{qs} = (\omega_r L^2_m i_{ds} + R_s L_r i_{qs} + \omega_r L_r L_m i_{dr} - R_r L_m i_{qr} - L_r v_{qs}) / a_0$$
$$\dot{i}_{dr} = -(R_s L_m i_{ds} - \omega_r L_m L_s i_{qs} - R_r L_s i_{dr} - \omega_r L_r L_m i_{qr} - L_m v_{ds}) / a_0$$
$$\dot{i}_{qr} = -(\omega_r L_m L_s i_{ds} + R_s L_m i_{qs} + \omega_r L_r L_s i_{ds} - R_r L_s i_{qr} - L_m v_{qs}) / a_0$$
$$a_0 = L^2_m - L_r L_s \tag{1}$$

The mathematical model of induction machine can also be rearranged with the stator and rotor currents set as the state variables as in equation (1). In terms of stator and rotor currents, the torque can be written as in (2)

$$T_e = (\frac{3}{2}\frac{p}{2} L_m)(i_{qs} i_{dr} - i_{ds} i_{qr}) \tag{2}$$

For the machine model created, inputs chosen were the stator voltage, the rotor speed, and the rotor resistance. The states chosen were the stator currents and rotor currents using the d-q (twin) axis model in the stationary reference frame. This gives the four electrical states. The outputs chosen were the stator and rotor currents and the "electrical" torque produced magnetic saturation effects were not included.

2.2 Mechanical Model

The mechanical model was created separately from the electrical model of the induction machine and is relatively simple as in equation (3)

$$T_e = T_L + \frac{2}{p} * J * \frac{d\omega r}{dt} \quad T_L + J\frac{d\omega_m}{dt} \tag{3}$$

Where T_L=load torque, J=rotor inertia, ω_r=rotor speed, and ω_m=mechanical speed

3. SVM BASED DTC

The basic principle of SVM based DTC is the direct selection of a space vector and corresponding control signals in order to regulate the electromagnetic torque and stator flux magnitude instantaneously. DTC provides very quick response with simple control structure and hence this technique is gaining popularity in industries [6]. 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 [24].

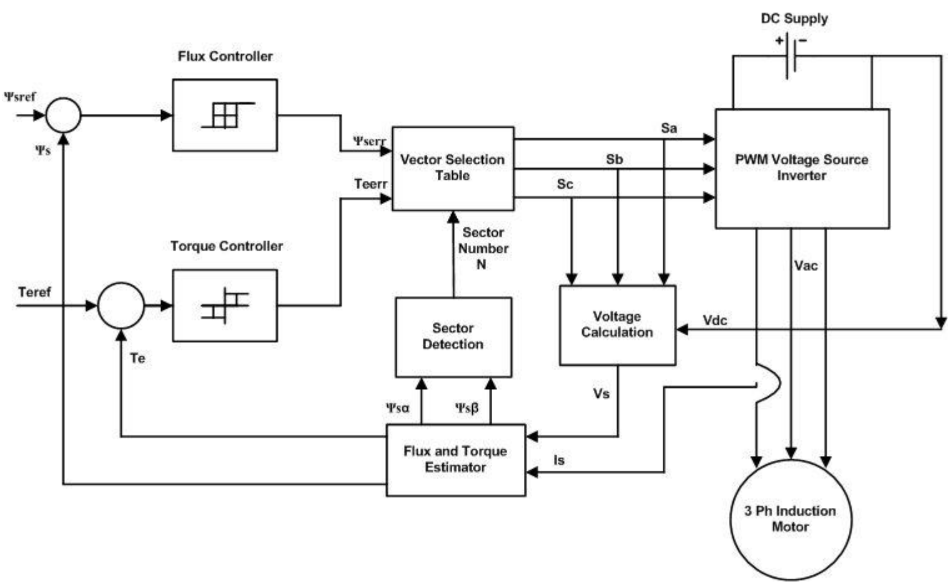

Figure 1 Basic scheme of PWM inverter fed induction motor with DTC.

The generic DTC scheme for a Voltage source PWM inverter-fed IM drive is shown in Figure1. 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 ($S_{A,}$ $S_{B,}$ S_C) which reduces the instantaneous flux and torque errors.

3.1 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 Figure 1. The command stator flux Ψ_{sref}, and torque T_{eref} values are compared with the actual Ψ_s and T_e 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 equations (4) and (5)

$$\psi_{serr} = 1,\ for\ \psi_s < \psi_{sref} - H_\psi \tag{4}$$

$$\psi_{serr} = -1,\ for\ \psi_s < \psi_{sref} + H_\psi \tag{5}$$

And those of the torque controller are as in equations (6), (7), (8),

$$T_{eerr} = 1,\ for T_e < T_{eref} - H_m \tag{6}$$

$$T_{eerr} = 0,\ for T_e = T_{eref} \tag{7}$$

$$T_{eerr} = -1,\ for T_e < T_{eref} + H_m \tag{8}$$

Where $2H_\Psi$ is the flux tolerance band and $2H_m$ is the torque tolerance band.
The digitized variables Ψ_{serr}, T_{eerr} and the stator flux section (sector) N obtained from the angular position

$$\alpha = \text{arctg}\ (\Psi_{s\beta} / \Psi_{s\alpha}) \tag{9}$$

create a digital word which is used to select the appropriate voltage vector. The stator voltage space vector V_s is calculated using the dc link voltage V_{dc} and the gating signals S_a, S_b, S_c as given in equation (10)

$$\overline{V}_s^s = \frac{2V_{dc}}{3}\left(S_a + e^{j2\Pi/3} S_b + e^{j4\Pi/3} S_c\right) \tag{10}$$

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. Figure 2 shows the relation of inverter voltage vector and stator flux switching sectors

TABLE 1 SWITCHING TABLE OF INVERTER VOLTAGE VECTORS

Ψ_{serr}	T_{eerr}	α(1) sect1	α(2) sect 2	α(3) sect 3	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
-1	1	V3	V4	V5	V6	V1	V2
	0	V0	V7	V0	V7	V0	V7
	-1	V5	V6	V1	V2	V3	V4

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. Therefore to obtain a good dynamic performance, an appropriate inverter voltage vectors V_i (i=1 to 6) has to be selected.

3.2 Stator Flux Control

By selecting the appropriate inverter output voltage V_i (i=1-6), the stator flux Ψ_s rotates at the desired frequency ω_s inside a specified band. If the stator ohmic drops are neglected, the stator voltage is directly proportional to the stator flux in accordance with the equations (11) and (12).

$$\bar{V}_s = \frac{d\bar{\psi}_s}{dt} \tag{11}$$

$$d\bar{\psi}_s = \bar{V}_s dt \tag{12}$$

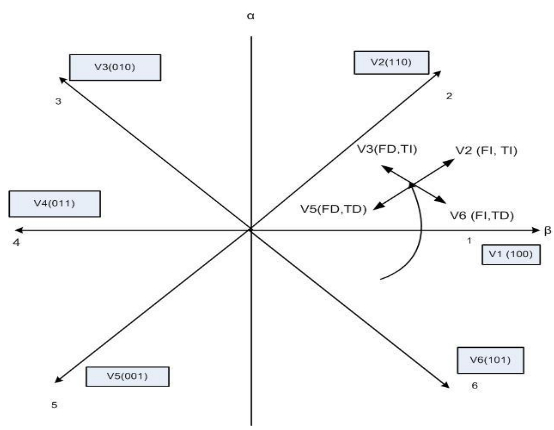

Figure 2 Stator flux vector locus and different possible switching voltage vectors. FD: flux decrease, FI: flux increase, TD: torque decrease, TI: torque increase.

Therefore the variation of the stator flux space vector due to the application of the stator voltage vector $\bar{V}_s$ during a time interval of Δt can be approximated as in equation (13).

$$\Delta\bar{\psi}_s = \bar{V}_s \Delta t \tag{13}$$

3.3 Torque Control

$$T_e = \frac{3}{2}\frac{p}{2}\frac{L_m}{L_r L_s^{'}}\psi_s \psi_r \sin\gamma \tag{14}$$

The electromagnetic torque given by equation (14) is a sinusoidal function of γ, the angle between Ψs and Ψ_r as shown in Figure 3. 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 (15).

$$\Delta T_e \cong \frac{3}{2}\frac{p}{2}\frac{L_m}{L_r L_s'}(\psi_s + \Delta\psi_s)\Psi_r \sin\Delta\gamma \tag{15}$$

Where $L_s' = L_s L_r - L_m^2$

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.

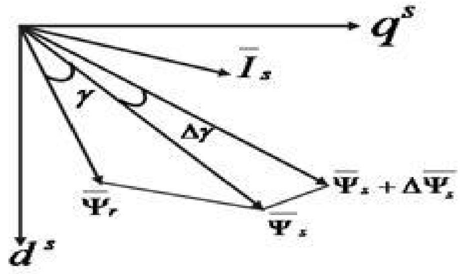

Figure 3 Stator flux and rotor flux space vectors

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 and the shaft position [25].

3.4 Stator Flux Estimation

In the stationary reference frame, the d and q axes stator fluxes are estimated based on equations (16), (17).

$$\overline{\psi}_{ds} = \int \left(\overline{V}_{ds} - \overline{i}_{ds} R_s\right) dt \tag{16}$$

$$\overline{\psi}_{qs} = \int \left(\overline{V}_{qs} - \overline{i}_{qs} R_s\right) dt \tag{17}$$

From this the magnitude and position of stator flux can be obtained from equations (18), (19)

$$\overline{\psi}_s = \sqrt{\overline{\psi}_{ds}^{\,2} + \overline{\psi}_{qs}^{\,2}}$$

(18)

$$\alpha = arctg\left(\frac{\psi_{qs}}{\psi_{ds}}\right) \tag{19}$$

3.5 Electromagnetic Torque Estimation

From the estimated stator flux and current components the electromagnetic torque of the motor is calculated as in equation (20)

$$T_e = 3\frac{p}{2}\left(\overline{\psi}_{ds}\overline{i}_{qs} - \overline{\psi}_{qs}\overline{i}_{ds}\right) \tag{20}$$

4. SIMULATION RESULTS AND DISCUSSIONS

4.1 *MATLAB Programming*

MATLAB/SIMULINK is a software package for modeling, simulating and analyzing dynamic systems. Figure 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).

TABLE 2 INDUCTION MACHINE PARAMETERS

Parameter	Symbol	Value
Stator resistance	R_s	1.85 Ω
Rotor resistance	R_r	1.84 Ω
Stator self inductance	L_s	170 mH
Rotor self inductance	L_r	170 mH
Mutual inductance	L_m	160 mH
Nominal Speed	ω_r	1440 rpm
Nominal Voltage	V_s	380 V
No of pole pairs	p	2

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 figure 5. The induction machine parameters used for simulation are given in table 2.

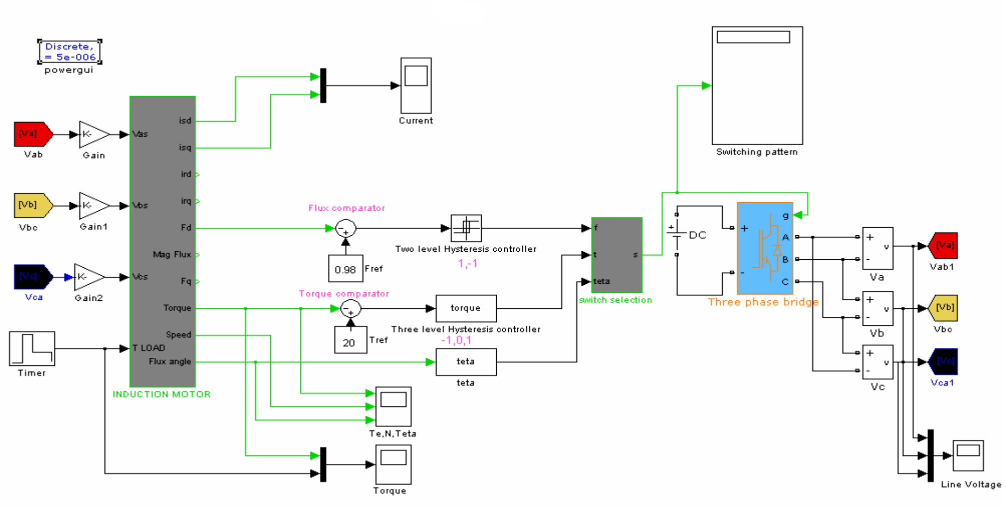

Figure 4 Simulink Model of Space Vector Modulation based Direct Torque Control

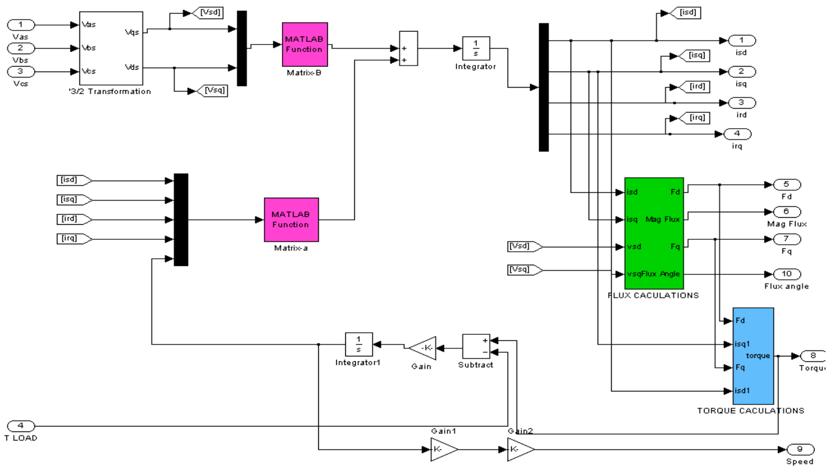

Figure 5 Simulink Model of Induction Machine

Simulation was carried out and the significance of SVM based DTC are proved. Simulation results of stator flux, electromagnetic torque, and speed are shown in figure 6, figure 7 and figure 8 respectively.

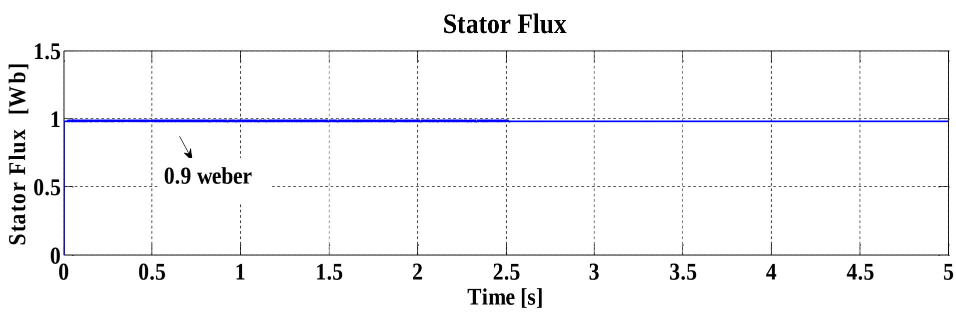

Figure 6 Simulation results of Stator flux

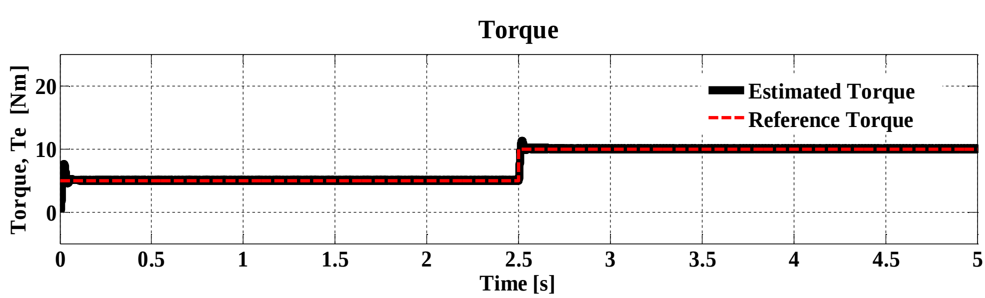

Figure 7 Simulation results of Electromagnetic Torque

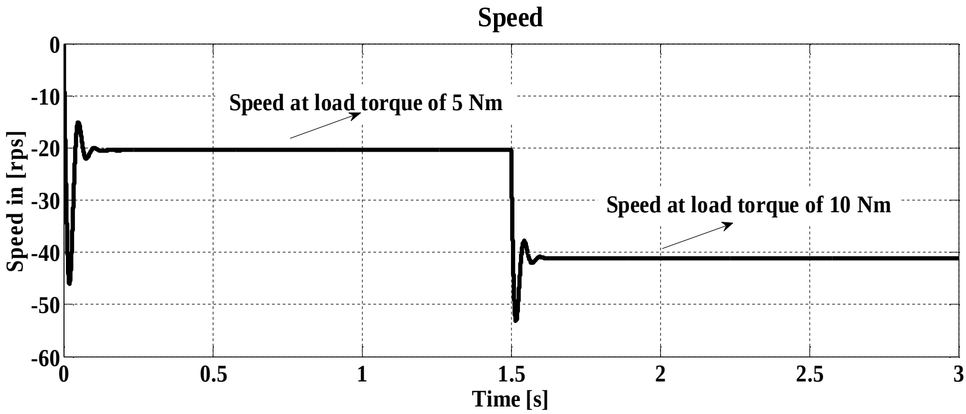

Figure 8 Simulation results of motor speed response

4.2 VHDL Programming

The complete system was modeled, simulated and evaluated using Xilinx / ModelSim environment using VHDL language. The design flow of VHDL programming is shown in figure. 9. The DTC algorithm is decomposed into several estimation as well as control blocks [26], [27]. The estimation blocks include stator flux, torque and voltage vector. The control blocks include two level and three level hysteresis comparators for flux and torque respectively, switching function and SVM block. Each module is described from hardware level using behavioural VHDL. The module should be decomposed into a number of VHDL entities that interface through VHDL ports. Each of these modules should be further subdivided into other modules. This decomposition process should be repeated until the remaining module become simple enough to be easy to test individually.

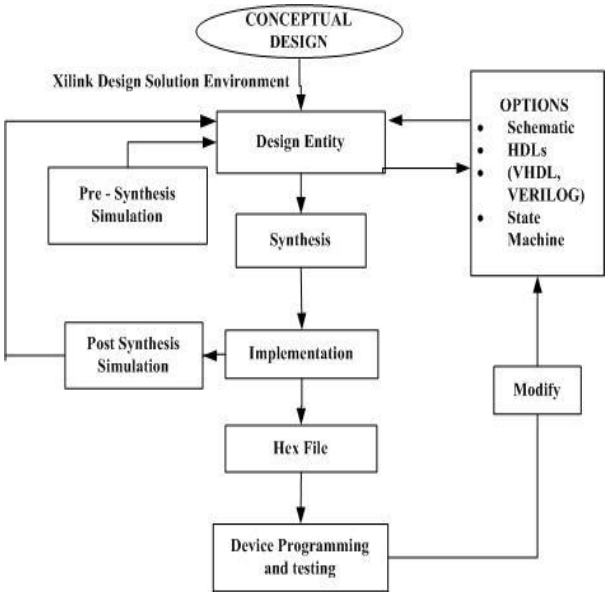

Figure 9 VHDL Programming Design Flow

4.3 Results and discussions

The functional block diagram of the DTC is shown in figure 10 (a). The SVM based DTC was developed and simulated using ModelSim 6.3 and the simulation results are shown in figures 10(b) & 10(c). The process of generating space vector consists of projection of a rotating vector on to six fundamental voltage vectors obtained by eight unique combinations of three phase switches. The rotating vector determines the time the projected vector is activated. This time is denoted as T_a and T_b. T_0 is null vector where either all the top switches are in on or off state.

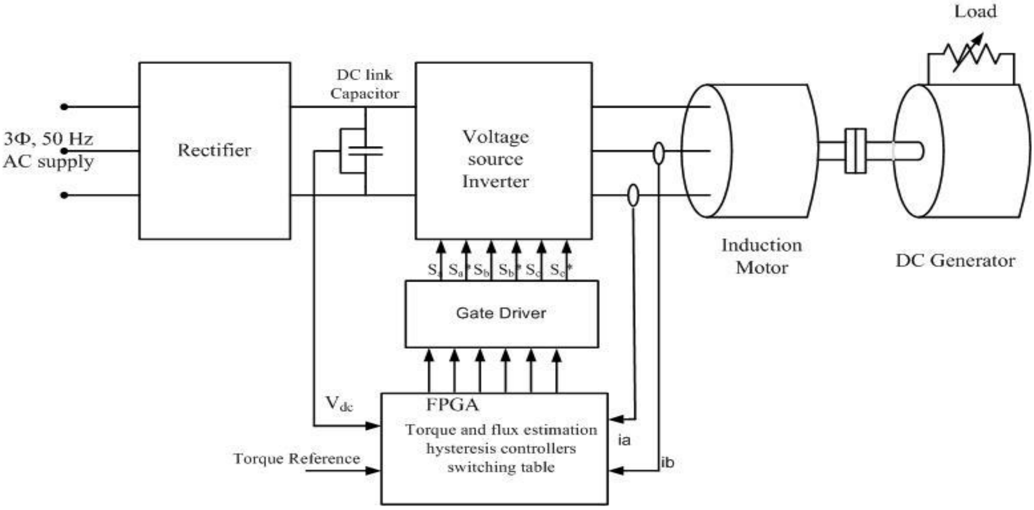

Figure 10(a) Functional Block diagram of SVM based DTC using FPGA circuits

FPGA implementation scheme uses interlocked time circuits to split the values of T_a, T_b & T_0. An LUT is used to turn on devices S1 – S6 based on the sector selection.

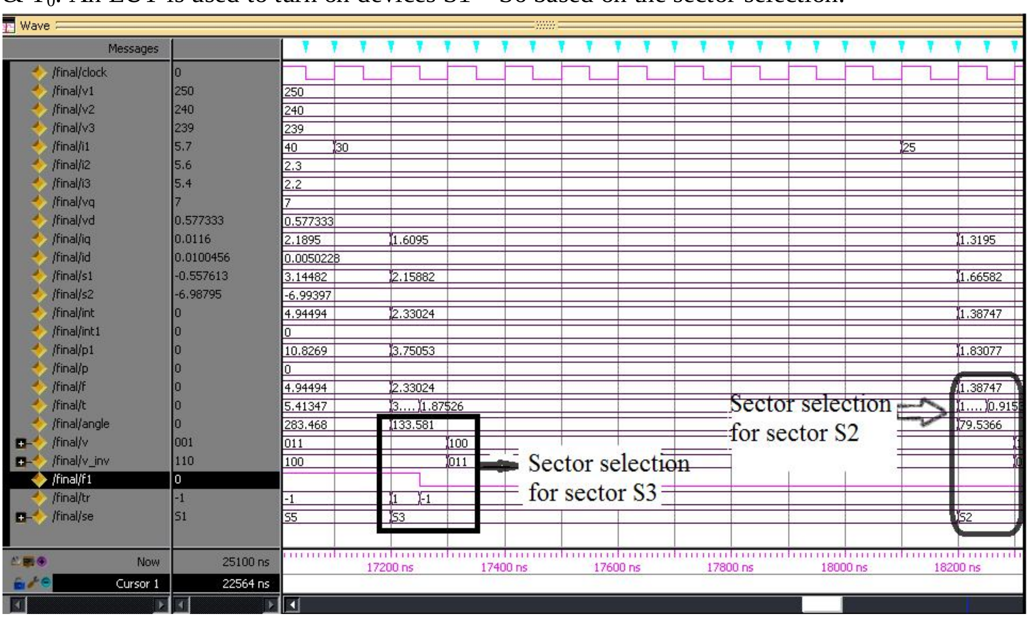

Figure 10(b) Simulation results showing the sector selection S2 for an angle 79.5 (60 ≥ α ≥ 120) and S3 for an angle 133.5(120≥ α ≥180)

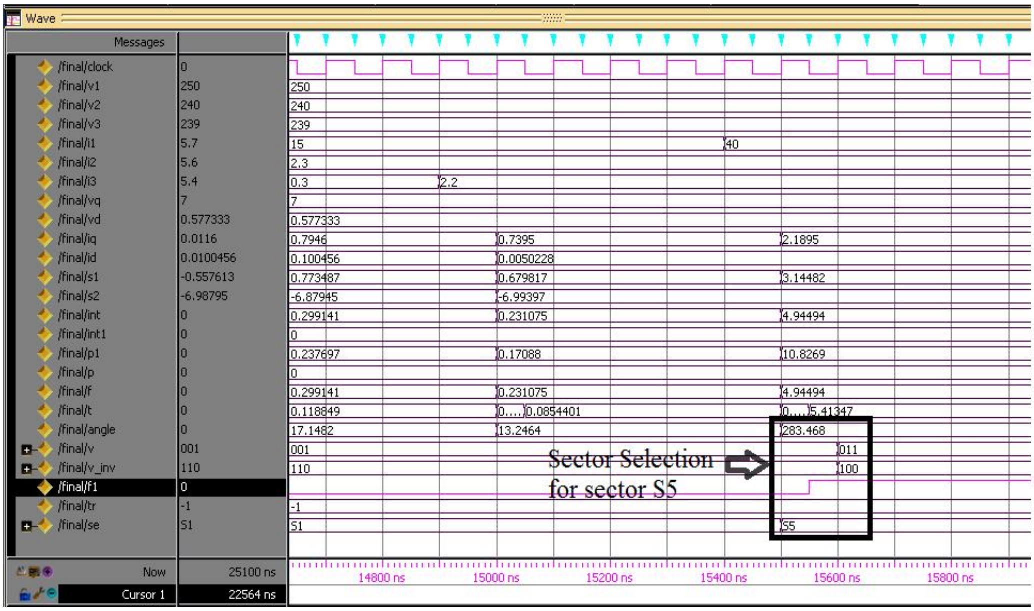

Figure 10 (c) Simulation results showing the sector selection S5 for an angle 283.4 (240< α< 300)

The simulation results proved the implementation of SVM based DTC by selecting proper sectors for various values of angle as estimated. The simulation result also showed the three phase (abc) to two phase (dq) transformation, stator flux and torque estimations.

5. CONCLUSION

In this paper SVM based DTC of an induction motor was simulated using MATLAB/SIMULINK platform as well as ModelSim / Xilinx platform. The voltage source inverter was controlled based on space vector modulation. The simulation results proved that the SVM, by proper sector selection based on the flux vector position results in low steady state torque ripples and current distortions. The proposed FPGA based DTC technique is expected to be a cost effective, high performance control technique useful in industries.

References

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

[2] J.W.Finch, and D.Giaouris, Controlled AC Electrical drives, *IEEE Transactions on Industrial Electronics*, 55(2), 481-491, 2008.

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

[4] F.Blaschke, A new method for the structural decoupling of A.C. induction machines, *in Conf. REC. IFAC*, Duesseldorf, Germany, 1–15, 1971.

[5] M.Depenbrock, Direct self-control (DSC) of inverter fed induction machine, *IEEE Trans. on Power Electronics*, 3, 420-429, 1988.

[6] T. Noguchi, and I.Takahashi, "Quick torque response control of an induction motor based on a new concept (in Japanese), *IEEJ Tech. Meeting Rotating Mach*., RM 84–76, 61–70,1984.

[7] I.Takahashi, and T.Noguchi, A new quick-response and high efficiency Control strategy of an induction machine, *IEEE Trans. Ind. Applications*, 22, 820– 827, 1986.

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

[9] H.F.Abdul Wahab, and H.Sanusi, Simullink Model of Direct Torque Control of Induction Machine, *American J. of Applied Sciences*, 5(8), 1083-1090, 2008.

[10] G.Buja, D.Casadei, and G.Serra, DTC- Based strategies for induction motor drives in *Proceedings of IEEE IECON'97,* 1997.

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

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

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

[14] M.Mengoni, L.Zarri, M.Tani, Serra, and Casadei, Stator flux vector control of induction motor drive in the field weakening region, *IEEE Trans. on Power Electronics*, 23, 941-949, 2008.

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

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

[17] Z.Zhifeng, T.Renyuan, B.Baodong, and X.Dexin, Novel Direct Torque Control Based on Space Vector Modulation with Adaptive Stator Flux Observer for Induction Motors, *IEEE Trans. on Magnetics*, 46(8), 3133- 3137, 2010.

[18] S.Ferreira, F.Haffner, L.F.Pereira, F.Moraes, Design and prototyping of Direct Torque Control of Induction Motors in FPGAs, *IEEE proceedings of 16th Symposium on Integrated Circuits and Systems Design*, Sao Paulo, Brazil, 105-110, 2003.

[19] L.Charaabi, E.Monmasson, A.Naasani, I.Slama-Belkhodja, and M.H.Belmimoun, Choosing FPGA or DSP for control algorithms; The case of the DTC, in *Pro. Electrimacs Conf,* 2005.

[20] A.Llor, B.Allard, X.Linshi, J.M.Retif, Comparison of DTC implementations for Synchronous Machines, *IEEE 35th Power Electronics Specialists Conference*, Aachen Germany, 5, 3581-3587, 2004.

[21] Marcelo F. Castoldi, Manoel L.Aguiar, Azauri A. O. Junior, Jose R.B.A.Monteiro, A rapid prototype design to investigate the FPGA based DTC strategy applied to the speed control of induction motors, *IEEE*, 955-960, 2006.

[22] Sarat Kumar Sahoo, G.Tulasi Ram Das, and Vedam Subrahmanyam, Implementation and simulation of Direct Torque Control scheme with the use of FPGA circuit, *ARPN J. of Engineering and Applied Sciences*, 3(2), 48-54, 2008.

[23] C.L.Toh, N.R.N.Idris, and A.H.M.Yatim, N.D.Muhamad, M.Elbuluk, Implementation of a new torque and flux controllers for Direct Torque Control (DTC) of induction machines utilizing Digital Signal Processor (DSP) and Field Programmable Gate Arrays (FPGA), *The 36th IEEE Power Electronics Specialist Conference*, PESCO5, Recife, Brazil, 2005.

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

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

[26] Eric Monmasson and Marcian N. Cristea, FPGA design methodology for industrial control systems – A Review, *IEEE Trans. on Industrial Electronics*, 54(4), 1832-1842, 2007.

[27] Rahul Dubey, Pramod Agarwal, M.K.Vasantha, Programmable logic devices for motion control – A Review, IEEE Transactions on Industrial Electronics, 54(1), 559-566, 2007.