FPGA Implementation of Direct Torque Control of Induction Motor

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Abstract- **This paper presents direct and independent torque control of induction motors using the technique called direct torque control (DTC), which is an on-off control scheme. Stator flux and the electromagnetic torque are directly controlled by applying the appropriate voltage vector from a look-up table. The simulation results for electro- magnetic torque, flux, stator currents and stability plot are shown for the various speed commands.**

Keywords— **AC motors, direct torque control (DTC), space vector modulation (SVM), voltage source inverters, flux and torque processor (FTP).**

I. INTRODUCTION

The induction motor is the most widely used electrical motor in industrial applications, due to their ruggedness and low price. The majority of induction machines are used in constant speed drives, but during the last decade the introduction of new semiconductor devices have made possible the use of induction motor as variable speed drives with induction machines available [1]. The Induction motor can be operated directly from mains, but variable speed and often energy efficiency are achieved by means of a frequency converter between mains and the motor. A typical frequency converter consists of a rectifier, a voltage stiff dc link or current stiff dc link and a pulse width modulated (PWM) inverter [2]. With the development in the power electronics area, the vector control methods, which uses fast microprocessors and DSP's, made possible the use of induction motors in typically DC motors dominating areas, since the current components producing torque and flux are decoupled, achieving the system separately excited DC motor similar features [3]. The direct torque control (DTC) method, developed by German and Japanese researchers allows direct and independent electromagnetic torque and flux control, selecting an optimal switching vector using a look-up table (which allows us eliminating the transformation blocks), making possible fast torque response, low inverter switching frequency and low harmonic losses [4].

The paper is organized as follows: Section 2 describes basic DTC scheme. Section 3 explains about the motor model. Hysteresis controllers and switching voltage vector selector is explained in section 4. Simulation results are presented in section5 followed by conclusion in Section 6.

II. BASIC DTC SCHEME

Direct Torque Control (DTC) is simple in construction yet superior in performance, when compared to vector control. Simply stated, DTC is a scheme where, when the flux and torque error is beyond the acceptable limit, appropriate switches of the inverter are closed to bring back the errors within the acceptable level. When the error is within acceptable level, no voltage is applied on the machine. DTC is simply an on/off control scheme so as to keep the stator flux and the electromagnetic torque within the acceptable level. Block diagram of conventinal DTC scheme is shown in Fig. 1.
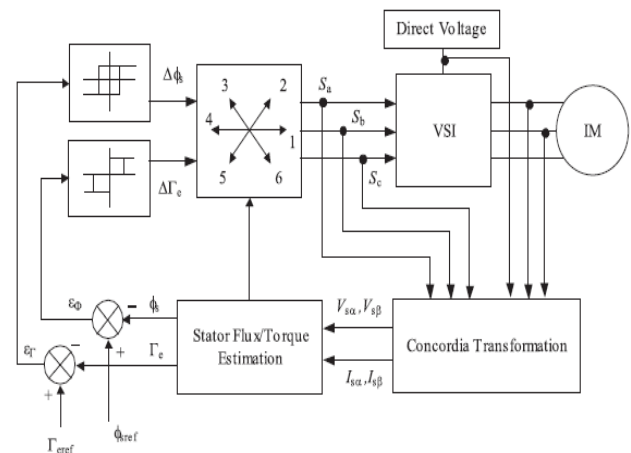

Fig 1: conventional DTC scheme [5]

Voltage vectors can be produced straight away from the flux and torque error-is the main idea of DTC. Similarly, the rotating to stationary frame transformation and 2 to 3 phase transformation are simply replaced by a look up table. This look up table simply gives appropriate voltage vector as output for the quantized value of flux and torque error and the sector of location of the stator flux as inputs. Based on the voltage vector selected appropriate switches are closed in the inverter. This is analogous to the hysteresis based current control in the case of Vector control.

Due to the absence of several controllers and the transformations in DTC, the delay in processing signal is drastically reduced; further the control is exercised by instantaneous Voltage vector in DTC. Sensorless Direct

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torque control is the latest advanced high performance drive control scheme because of the advantage that the speed sensor, which is expensive, fragile and requires extra cabling, is not needed for closed loop control of Induction motor drives, which is cheaper when compared with any other type of control. It can be defined as a scheme in which stator flux and electromagnetic torque are directly controlled by the application of the appropriate voltage vector from a look up table.

The vector control technique did not immediately take off because of the non-availability of fast digital signal processors at that time. Considering the lot of interest shown by the research community in Vector Control and Direct Torque Control and with the decreasing cost of the hardware, it can be safely predicted that AC Drives with Vector control or the DTC technique would eventually replace the DC Drives. Among Vector Control and DTC, the simplicity and the superior performance of DTC would make it more popular, if some of the advantages like high ripple, variable switching frequency are removed.

III. MOTOR MODEL

Induction motor can be modeled by the set of equationsgiven below where all quantities are referred as either with respect to stator or rotor. The three phase voltage vectors from the output of the inverter can be considered as V_{as}, V_{bs}, V_{cs} and from which we can convert the d and q components of the stator voltages are given by

$$Vds = 2/3(Vas -0.5Vbs -0.5Vcs) \tag{1}$$
$$Vqs = 2/3(\sqrt{3}/2\ Vbs + \sqrt{3}/2\ Vcs) \tag{2}$$

From these quantities as input we can model d and q components of fluxes w.r.t stator and rotor can obtained

$$\Psi ds = \int(Vds- Ids\ Rs)dt \tag{3}$$
$$\Psi qs = \int(Vqs- Iqs\ Rs)dt \tag{4}$$
$$\Psi dr = \int(-\omega r .\Psi qr - Idr . Rr)dt \tag{5}$$
$$\Psi qr = \int(-\omega r .\Psi dr – Iqr . Rr)dt \tag{6}$$

From these quantities we can estimate the currents and the mechanical parameters like electromagnetic torque and machine speed

$$Ids = (\Psi ds - \Psi dr . Lm/Lr) /(Ls-Lm2/Lr) \tag{7}$$
$$Iqs = (\Psi qs - \Psi qr . Lm/Lr) /(Ls-Lm2/Lr) \tag{8}$$
$$Idr = (\Psi dr - \Psi ds . Lm/Ls) /(Lr-Lm2/Ls) \tag{9}$$
$$Iqr = (\Psi qr - \Psi qs . Lm/Ls) /(Lr-Lm2/Ls) \tag{10}$$
$$Te = 3/2*P*(\Psi ds\ Iqs - \Psi qs\ Ids) \tag{11}$$
$$\omega r = 1/J \int (Te-TL)\ dt \tag{12}$$

With the help above motor equations we can model an induction motor and simulate the same in the MATLAB/SIMULINK.

IV. HYSTERESIS CONTROLLERS AND SWITCHING VOLTAGE VECTOR SELECTOR

The Torque Hysteresis controller is used to control the load angle or field angle γ between the rotor and the stator flux; while the flux hysteresis controller is used to control the magnitude of the stator flux within the flux hysteresis controller is used to control the magnitude of the stator flux within the flux hysteresis controller. The torque and flux errors obtained by comparing estimated values with reference values are processed in the three level and two level comparators. The hysteresis controllers are shown in Fig 2 and 3.
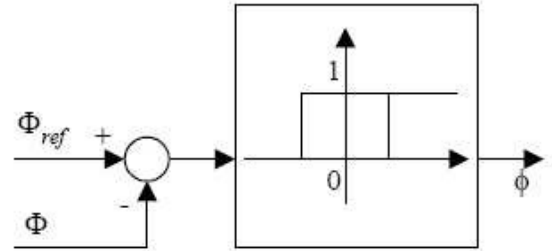

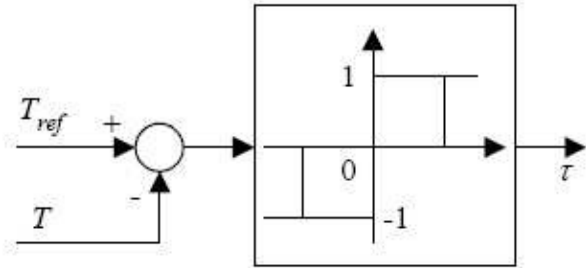Fig 2: Two level hysteresis comparator: φ= 1 → increase flux; φ= 0 → decrease flux [4].

Fig 3: Three level hysteresis comparator: τ=1→ increase torque; τ=0→ maintain torque; τ=-1→decrease torque [4].

The switching voltage vector selector block determines the switching voltage vector and output the voltage to be applied to the motor depending on the hysteresis controller outputs. he knowledge of the sector in which the stator flux linkage space vector is lying is essential to determine the optimum voltage vector.

$$Sector\ 1 : (\psi_{ds} \sqrt{3} \geq \psi_{qs})\ \&\ (\psi_{ds} \geq 0)$$
$$Sector\ 2 : (\psi_{ds} \prec \sqrt{3}\psi_{qs})\ \&\ (\psi_{ds} \geq 0)$$
$$Sector\ 3 : (| \psi_{ds} |< \sqrt{3}\psi_{qs})\ \&\ (\psi_{ds} \prec 0)$$
$$Sector\ 4 : (| \psi_{ds} |\geq \sqrt{3}\psi_{qs})\ \&\ (\psi_{ds} < 0)$$
$$Sector\ 5 : (\psi_{ds} \leq \sqrt{3} | \psi_{qs} |)\ \&\ (\psi_{ds} \prec 0)\ \&\ (\psi_{qs} < 0)$$
$$Sector\ 6 : (\psi_{ds} < \sqrt{3} | \psi_{qs} |)\ \&\ (\psi_{ds} \geq 0)\ \&\ (\psi_{qs} < 0)$$

The switching vector is selected as per the following look-up table for the voltage vector positions U1 to U8 depending on the hysteresis comparator outputs.

τ	φ	θ1	θ2	θ3	θ4	θ5	θ6
+1	1	V_2	V_3	V_4	V_5	V_6	V_1
0	1	V_7	V_0	V_7	V_0	V_7	V_0
-1	1	V_6	V_1	V_2	V_3	V_4	V_5
+1	0	V_3	V_4	V_5	V_6	V_1	V_2
0	0	V_0	V_7	V_0	V_7	V_0	V_7
-1	0	V_5	V_6	V_1	V_2	V_3	V_4

Fig 4: Optimum Voltage Switching Vector Look Up Table[4].

U1 (100), U2 (010), U3 (110), U4 (011), U5 (00l), U6 (10l) are active voltage switching vectors and U7 (111), U8 (000) are zero voltage switching vectors.

The locus of the stator flux is divided into minimum six sectors as six-pulse inverter is used. In a sector, the voltage vector that is oriented towards the upper flux hysteresis band is the flux increasing voltage vector, while the voltage vector that is oriented towards the lower flux hysteresis band is the flux decreasing voltage vector. In the same way, the voltage vector that increases the angle between the stator flux and the rotor flux is the torque increasing voltage vector, while the voltage vector that decreases the angle between the stator flux and the rotor flux is the torque decreasing voltage vector. The voltage vector that does not significantly increase or decrease the angle between the stator and the rotor flux is neglected in that particular sector.
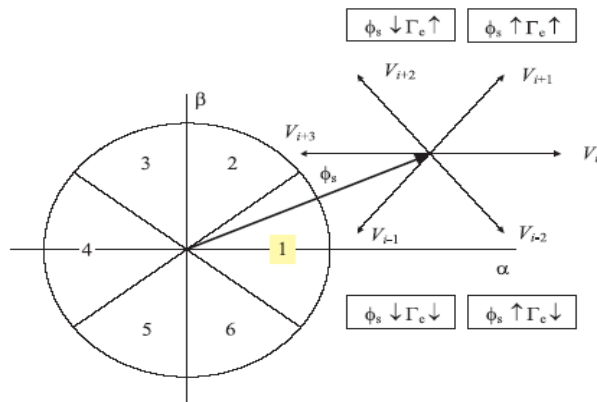

Fig 5: selection of switching voltage vector [5]

The vector diagram of selection of switching voltage vector is shown in Fig 5 from the vector diagram, it can be identified that the U2 and U6 are the flux increasing voltage vector, while U3 and U5 are the flux decreasing voltage vector. Similarly applying the condition of angle-increase or ngledecrease, for finding the torque increasing or decreasing voltage vector, it can be identified that U2 and U3 are the torque-increasing voltage vector, while U5,U6 are the torque

decreasing voltage vector. For the torque error within the acceptable limit, torque zero voltage vectors, either U7 or U8 are applied. Of the two, the one which minimizes the switching is chosen. In the same way, for other sector also the voltage vectors are found and the optimum voltage switching vector look-up table is formed as shown in Table.

V. SIMULATION RESULTS

A simulation on the DTC drive is carried out using Matlab/Simulink simulation package. Using the systemgenerator of the Xilinx Virtex-3 DSP builder, VHDL code is generated and simulated. The IM used for the simulation and experiment is a standard 50 Hz,415/240V squirrel cage Induction motor. Fig 6 shows the speed and torque response for the given speed command.
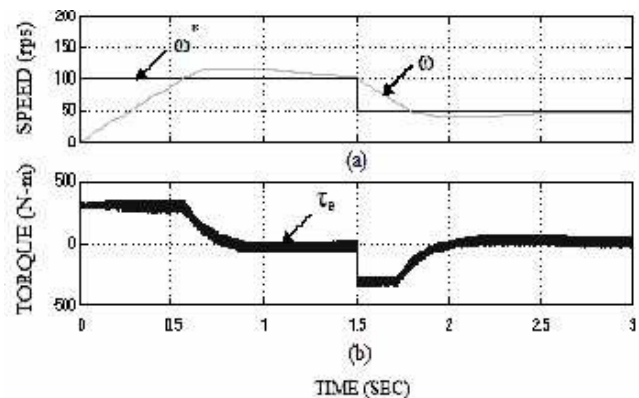

Fig 6. shows performance of 4-pole, 50hz, 1.5kw squirrel cage induction motor (a) speed reference and motor speed (b) electromagnetic torque.
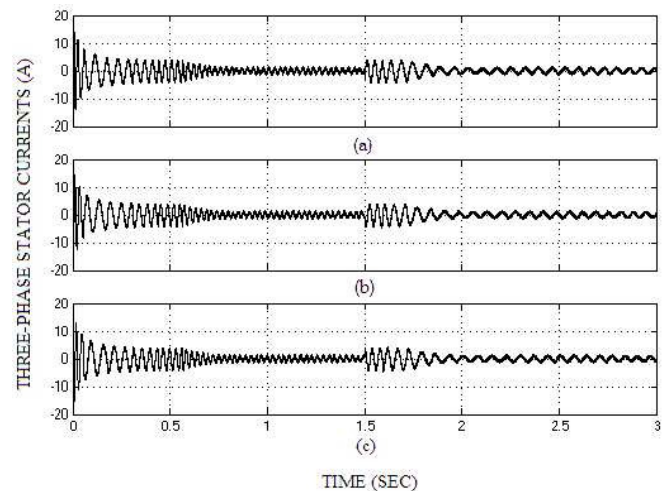

Fig 7 shows the fluctuation in the stator phase currents for the given speed reference, (a), (b) & (c) are the three phase stator currents respectively.
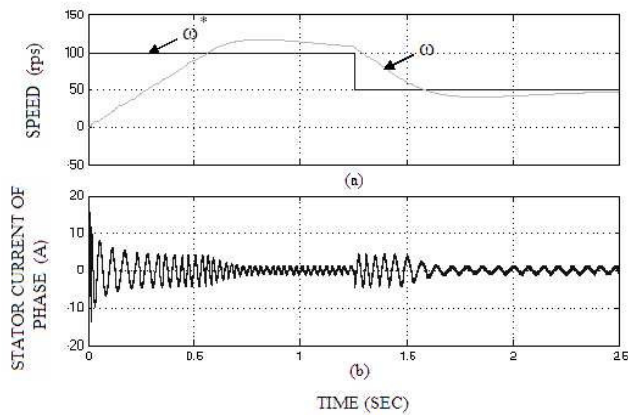
Fig 8 shows variation in the stator current for decrease in speed command, (a) reference speed & motor speed, (b) stator current (a- phase).
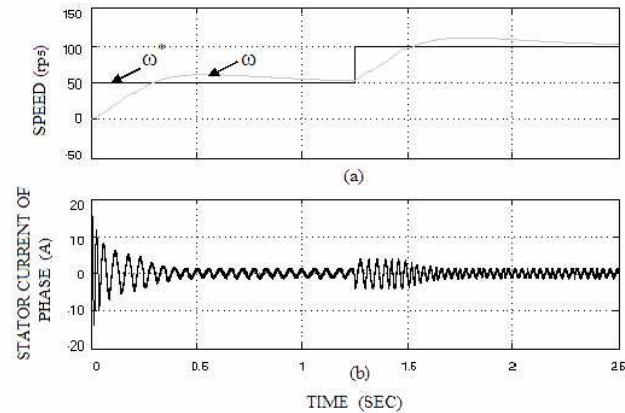

Fig 9 shows variation in the stator current for increase in speed command, (a) reference speed & motor speed, (b) stator current (a- phase).
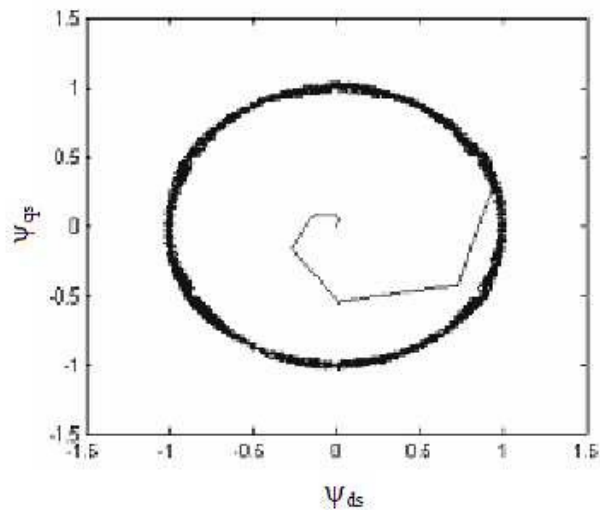

Fig 10 shows the stability plot which plotted between quadrature axis flux and direct axis flux.

This stability plot will comment on the system stability at all load conditions and external disturbances, if the plot lies between the unit circle then the system is in stable state.

VI. CONCLUSION

The complete model of sensor less direct torque control of an induction motor drive has been developed using Matlab/Simulink. The stator flux and electromagnetic torque equations are developed from voltage model equations. The simulation results of conventional DTC drive are simulated. From the simulation results it is observed the flux ripples and torque ripples are greatly reduced. And we have several advantages that, quick torque response, absence of separate voltage modulation and coordinate transformation block. It also suffers with certain corns like, requirement of flux and torque estimators, high ripple torque, and variable switching frequency.

APPENDIX

The implemented equations were validated with the Standard Induction machine in the library of power system toolbox in MATLAB/SIMULINK. The rating and motor parameters of the induction motor drive chosen for the design of conventional and artificial based controllers are given elow. The parameters of the induction machine used for simulation is given in the following table.

Motor Parameters

Parameters	Values
Stator Resistance (R_s)	3.67Ω
Rotor Resistance (R_r)	2.32Ω
Magnetizing Inductance (L_m)	0.235H
Stator Inductance (L_s)	0.245H
Rotor Inductance (L_s)	0.248H
Inertia J	0.0126Kg/m^2
Rotor Speed	1430 rev/min
Rated Current	5.0Amps
Rated Torque	14.6Nm

Inverter parameters

Electrical Quantity	Rating
Power	Voltage
25KW	400V-AC

HARDWARE IMPLEMENTATION OF FTP:

Flux and torque processor (FTP) can be implemented by using the motor model equations. And these equations are implemented in MATLAB/DSP BUILDER.
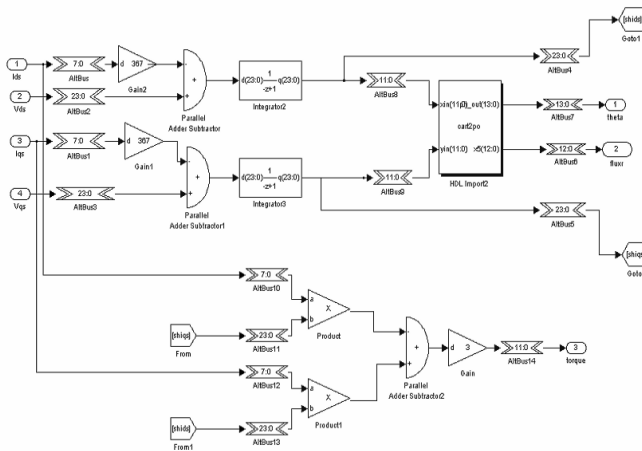
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Fig 11 shows implementation of flux and torque processor using
MATLAB/SIMULINK/DSP PROCESSOR.

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