

Simulation and Analysis of Direct Torque Controlled Induction Motor

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Abstract: This paper presents the Simulation of Direct Torque Control (DTC) algorithm for Induction Motor Drives using Very high speed integrated circuits Hardware Description Language (VHDL). A binary format is used with variable word size approach, which permits to reduce the calculation processes resulting in smaller errors without increasing hardware area in the prototyping of DTC Control. The results of VHDL Simulation for the DTC using Xilinx are presented.

Keywords: Direct Torque Control, VHDL, VSI, Induction Motor

1. Introduction

DC motors have been used during the last century in industries for variable speed control applications, because its flux and torque can be controlled easily by means of changing the field and armature currents respectively. Furthermore, operation in the four quadrants of the torque speed plane including temporary standstill was achieved. The advancement of power electronics has made it possible to vary the frequency of the voltage supplies relatively easy, thus has extended the use of induction motor in variable speed drive applications [1]. But due to the inherent coupling of flux and torque components in induction motor, it could not provide the torque performance as good as the DC motor.

The DTC scheme requires flux linkage and electromagnetic torque estimators. However, it is not necessary to monitor the stator voltage since they can be reconstructed by using the inverter switching modes and the monitored d.c links voltage. The electromagnetic torque can be estimated by using closed loop speed control can be obtained by using a speed controller whose output gives the torque reference, and the input to the speed controller is the difference between the reference speed and the actual speed. The required optimal switching voltage vectors can be selected by using a so called optimum switching voltage vector look up table. The simulation waveforms of DTC are not presented in the literature [1-14]. In the present work an attempt is made to simulate DTC system.

2. DTC Principle

Figure 1 shows the schematic of one simple form of the DTC induction motor drive, employing a voltage source inverter (VSI). In this scheme the stator flux is the controlled flux, thus it will be referred to as a stator flux based DTC induction motor drive. The voltage source six pulse inverter fed stator flux based DTC induction motor drive is shown [3]. Direct torque control involves the separate control of the stator flux and the torque through the selection of optimum inverter switching modes the optimum switching table had been shown in Table 1. The reference value of the stator flux linkage space vector modules is compared with the actual modulus of the stator flux linkage space vector and the resulting error is fed into the two level starter flux hysteresis comparator. Similarly,

the reference value of the electromagnetic torque is compared with the actual value and the electromagnetic torque error signed is into the three level torque hysteresis comparator. The outputs of the flux and torque comparators are used in the inverter optimal switching table which also uses the information on the position of the stator flux linkage space vectors [5]. The flux linkage and electromagnetic torque error are restricted within their respective hysteresis bands.

The DTC drive consists of DTC controller, torque and flux calculator, and a voltage source inverter. The configuration is much simpler than the FOC system due to the absence of frame transformer, pulse width modulator and position encoder, which introduce delays and requires mechanical transducer. The implementation of DTC is simple in structure and requires a fast processor to perform on-line calculations of electromagnetic torque and stator flux based on sampled terminal variables [7]. If a three phase VSI is connected to an induction motor, there can be eight possible configurations of six switching devices within the inverter. As a result, there are eight possible input voltage vectors to the induction motor.

DTC utilizes the eight possible stator voltage vectors, two of which are zero vectors, to control the stator flux and torque to follow the reference value within the hysteresis bands. The voltage space vector of a three-phase system is given by:

$$\bar{v}_s(t) = 2/3(v_{sA}(t) + av_{sB}(t) + a^2v_{sC}(t)), \quad (1)$$

$$\text{where } a = e^{j2/3\pi}$$

Counter Clockwise		Sec I	Sec II	Sec III	Sec IV	Sec V	Sec VI
Inc Flux (0)	Inc T(01)	100	110	010	011	001	101
	Dec T(00)	000	111	000	111	000	111
Dec Flux (1)	Inc T(01)	110	010	011	001	101	100
	Dec T(00)	111	000	111	000	111	000

Clockwise		Sec I	Sec II	Sec III	Sec IV	Sec V	Sec VI
Inc Flux (0)	Inc T(10)	001	101	100	110	010	011
	Dec T(00)	000	111	000	111	000	111
Dec Flux (1)	Inc T(10)	011	001	101	100	110	010
	Dec T(00)	111	000	111	000	111	000

Table 1: Switching Table

V_{sA} , V_{sB} , and V_{sC} are the instantaneous phase voltages. For the switching VSI, it can be shown that for a DC link voltage of V_d , the voltage space vector is given by:

$$\bar{V}_s(t) = \frac{2}{3} V_d (S_a(t) + S_b(t)a + S_c(t)a^2) \quad (2)$$

$S_a(t)$, $S_b(t)$ and $S_c(t)$ are the switching functions of each leg of the VSI, such that,

$$S_i = \begin{cases} 1 & \text{when upper switch is on} \\ 0 & \text{when lower switch is on,} \end{cases} \quad i = a, b, c$$

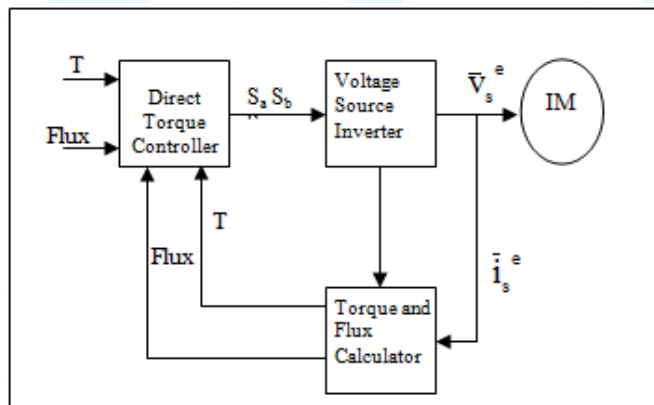


Figure 1: Principle of DTC

where ω_{sl} is the angular slip frequency of the stator flux with respect to the rotor mechanical frequency. This means that the rate of change of torque can be made positive or negative regardless of whether the stator flux is increasing or decreasing. If the torque and stator flux is kept within their hysteresis bands by selecting appropriate voltage vectors, an independent control over the torque and stator flux is accomplished. If the stator flux space vector plane is divided into six sectors or segments as shown in Figure 3, a set of table of which voltage vector should be chosen in a particular sector (either to increase stator flux or to reduce stator flux and either to increase torque or to reduce torque) can be constructed.

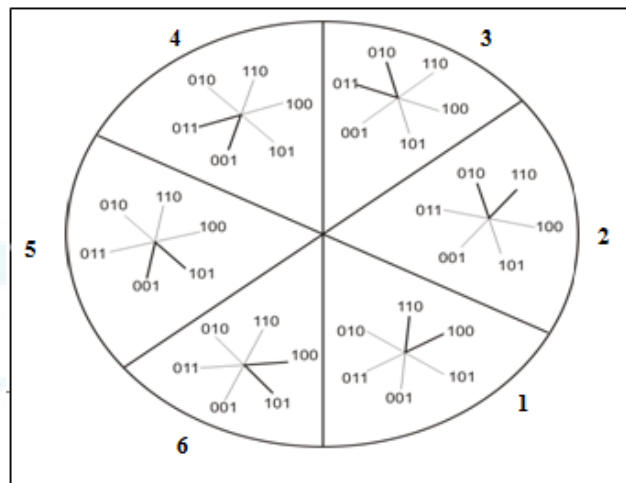


Figure 2: Sectors of Stator Flux Plane

3. DTC Architecture

DTC algorithm is implemented in an architecture composed by five main blocks: motor model, flux comparator, sector evaluation, torque comparator and switching table. The available processing time is dictated by the A/D converters, corresponding to 25µs. This time interval is partitioned into five time slots, allowing for the processing of input samples. The motor model module uses time slots 1 to 3. In the first time slot (i_{d1}) 16-bit samples are read from the A/D converters. Modules flux comparator, sector evaluation and torque comparator are processed in parallel in the fourth time slot, while last time slot is used to compute the switching table (Ch_a, Ch_b, Ch_c). Motor model module has three 16-bit inputs supplied by A/D converters: i_1, i_2 and V_d and produces four outputs: torque, $\lambda_\alpha, \lambda_\beta$ and λ_{mod} . The motor modeling equations are implemented according to the architecture. As can be observed, complex mathematical operations are performed such as multiplications and a square root. Sector evaluation is a module that receives stator flux components as inputs and determines the position of the flux vector in a plane divided into six sectors denominated sectors 1 to 6. To determine the position of stator flux, magnitude is compared with projection components in the axes α and β .

4. Simulation Results

The DTC architecture is simulated using Xilinx Package. The results of flux comparator are shown in figure 4. The results of torque comparator and sector evaluator are shown in figure 5 & 6. The switching table wave forms are shown in figure 7. The simulated wave forms of control signals are shown in figure 8. The results of DTC blocks are shown in figure 9. The actual torque is compared with set torque and the actual flux is compared set flux. The pulse width of the driving pulse is selected such that actual torque is equal to set torque. From the simulation results it is observed that the motor develops a torque equal to the set torque.



Figure 3: Flux Comparator

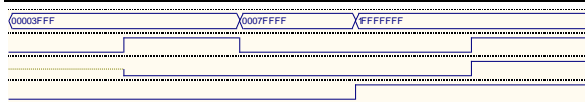


Figure 4: Torque Comparator

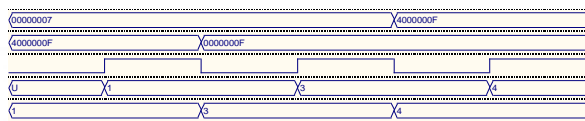


Figure 5: Sector Evaluator

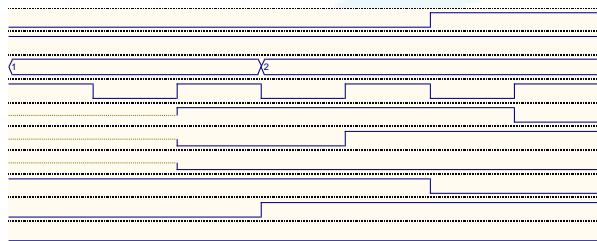


Figure 6: Switching Table

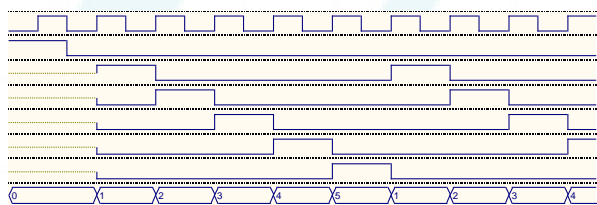


Figure 7: Control Signals

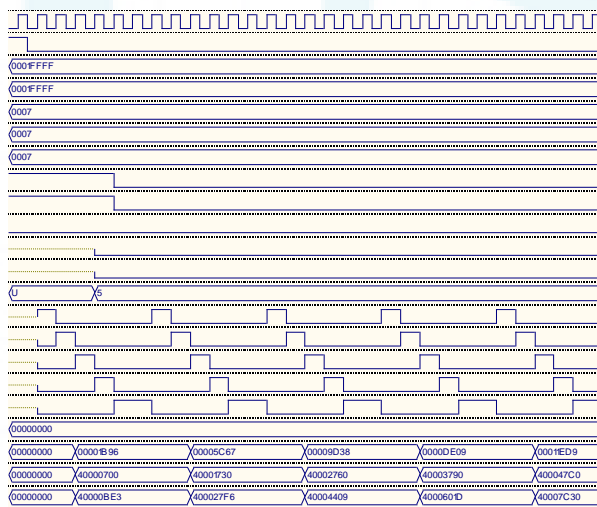


Figure 8: DTC

5. Conclusion

The architecture proposed is written in synthesizable VHDL. The actual torque is compared with set torque and the actual flux is compared set flux. The pulse width of the driving pulse is selected such that actual torque is equal to set torque. From the simulation results it is observed that the motor develops a torque equal to the set torque.

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