

# High Performance Direct Torque Control of Induction Motor Drives Using Space Vector Modulation

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## Abstract

This paper presents a simple approach to design and implement Direct Torque Control technique for voltage source inverter fed induction motor drives. The direct torque control is one of the excellent strategies available for torque control of induction machine. It is considered as an alternative to field oriented control technique. The Direct Torque Control scheme is characterized by the absence of PI regulators, co-ordinate transformations, current regulators and pulse width modulated signal generators. Direct Torque Control allows a good torque control in steady state and transient operating conditions. The direct torque control technique based on space vector modulation and switching table has been developed and presented in this paper.

**Keywords:** Direct Torque Control (DTC), Space Vector Modulation (SVM), 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.

Induction motor control methods can be broadly classified into scalar control and vector control. Scalar control based

on relationships valid in steady state conditions. Only magnitude and frequency (angular speed) of voltage,

current, and flux linkage space vectors are controlled. Thus, the scalar control does not act on space vector position during transients. Vector control is based on relations valid for dynamic states, not only magnitude and frequency (angular speed) but also instantaneous positions of voltage, current, and flux space vectors are controlled. Thus, the vector control acts on the positions of the space vectors and provides their correct orientation both in steady state and during transients.

In scalar control, V/F control is the important control technique, it is the most widespread, reaching approximately 90% of the industrial applications [2]. It acts imposing a constant relation between voltage and frequency. The structure is very simple and it is normally used without speed feedback, hence this control does not achieve a good accuracy in both speed and torque responses mainly due to the fact that the stator flux and the torque are not directly controlled. The speed can be 2% (except in a very low speed) and the dynamic response can be approximately around 50ms.

The vector control is most popular method; known as *field-oriented control* (FOC) gives the induction motor high performance. In the vector control the motor equations are transformed in a coordinate system that rotates in synchronism with the rotor flux vector. These new coordinates are called *field coordinates*. In field coordinates under constant rotor flux amplitude, there is a *linear* relationship between control variables and torque similar to a separately excited dc motor. These coordinate transformations are selected to achieve decoupling and linearization of induction motor equations. Main advantages of vector controllers include good accuracy such as 0.5% regarding the speed and 2% regarding the torque, even in stand still. The main disadvantages are the

huge computational capability required and the compulsory good identification of the motor parameters [3].

The method proposed to replace the de-coupling control with the bang-bang control, which meets very well with on-off operation of the inverter semiconductor power devices is referred to as *direct torque control* (DTC) [5]. The DTC also exploits the vector relationships but replaces the coordinate transformation concept of standard vector control with a form of bang - bang action, dispensing from *pulse width modulation* (PWM) current control [6]. In DTC the bang-bang or hysteresis controllers impose the time duration of the active voltage vectors, moving stator flux along the reference trajectory.

The key features of DTC compared to standard vector control includes

- No current loops so current not directly regulated
- Coordinate transformations not required
- No separate voltage pulse width modulator
- Stator flux vector and torque estimation required.

Recent advancements in DTC systems include the use of unified flux control scheme [11], stator flux vector control in field weakening region [14], torque ripple minimization techniques [12], space vector modulation (SVM) technique [7], neuro - fuzzy [15], FPGA [13].

The purpose of this paper is to review the simulation of DTC technique using MATLAB/SIMULINK model.

## 2. Principle of Direct Torque Control

DTC provides very quick response with simple control structure and hence this technique is gaining popularity in

industries [8], [10]. 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 [4].

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 ( $S_A, S_B, S_C$ ) which reduces the instantaneous flux and torque errors.

## 3. Basic Switching Table and Selection of Voltage Vectors

The basic idea of the switching table DTC concept is shown in Fig. 1. The command stator flux  $\Psi_{sref}$  and torque  $T_{eref}$  values are compared with the actual  $\Psi_s$  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 (1) and (2)

$$\psi_{serr} = 1, \text{ for } \psi_s < \psi_{sref} - H_\psi \quad (1)$$

$$\psi_{serr} = -1, \text{ for } \psi_s < \psi_{sref} + H_\psi \quad (2)$$

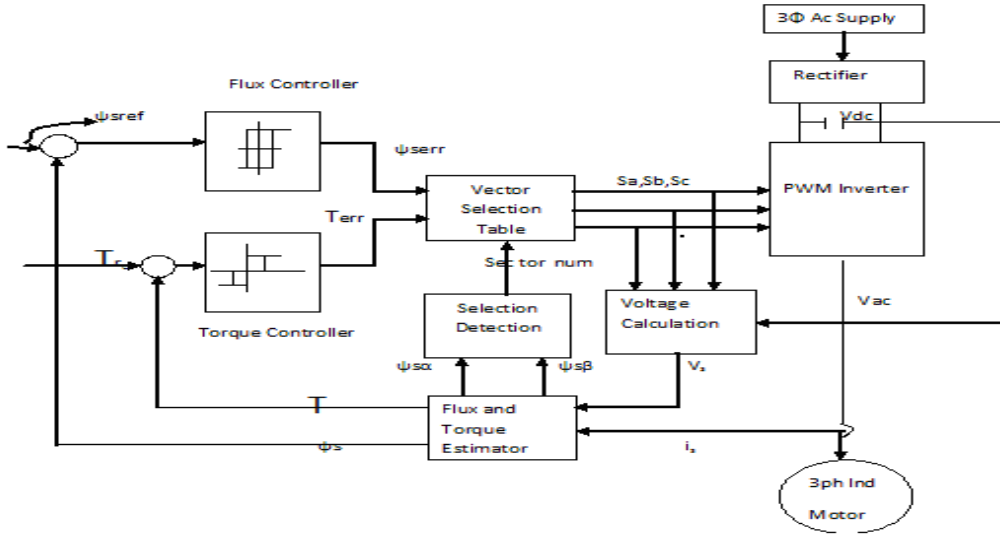


Fig. 1 Basic scheme of PWM inverter fed induction motor with DTC

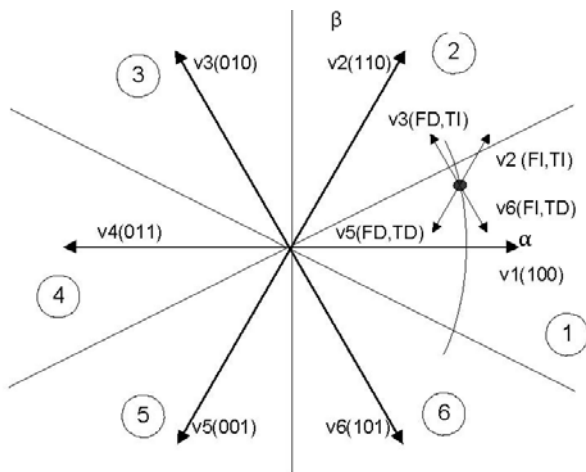


Fig. 2 Inverter voltage vectors and stator flux switching sector

And those of the torque controller as in equations (3), (4), (5),

$$T_{err} = 1, \text{ for } T_e < T_{eref} - H_\psi \quad (3)$$

$$T_{err} = 0, \text{ for } T_e = T_{eref} \quad (4)$$

$$T_{err} = -1, \text{ for } T_e < T_{eref} + H_\psi \quad (5)$$

where  $2H_\psi$  is the flux tolerance band and  $2H_m$  is the torque tolerance band. The digitized variables  $\Psi_{serr}$ ,  $T_{err}$  and the stator flux section (sector) N, obtained from the angular position

$$\alpha = \arctg(\Psi_{s\beta} / \Psi_{sa}) \quad (6)$$

create a digital word where,

$$-30^\circ < \alpha(1) < 30^\circ$$

$$30^\circ < \alpha(2) < 90^\circ$$

$$90^\circ < \alpha(3) < 150^\circ$$

$$150^\circ < \alpha(4) < 210^\circ$$

$$210^\circ < \alpha(5) < 270^\circ$$

$$270^\circ < \alpha(6) < 330^\circ$$

On the basis of torque and flux hysteresis status and the stator flux switching sector, which is denoted by  $\alpha$ , DTC algorithm 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 [3]. Therefore to obtain a good dynamic performance, an appropriate inverter voltage vectors  $V_i$  ( $i=1$  to 6) has to be selected.

Table 1: Switching table of Inverter Voltage Vectors

$\Psi_{serr}$	$T_{err}$	$\alpha(1)$	$\alpha(2)$	$\alpha(3)$	$\alpha(4)$	$\alpha(5)$	$\alpha(6)$
		sect 1	sect 2	sect 3	sect4	sect5	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	V3	V4	V5	V6	V1	V2
0	0	V0	V7	V0	V7	V0	V7
	-1	V5	V6	V1	V2	V3	V4

### 3.1. Stator Flux Control

By selecting the appropriate inverter output voltage  $V_i$  ( $i=1-6$ ), the stator flux  $\Psi_s$  rotates at the desired frequency  $\omega_s$  inside a specified band. If the stator ohmic drops are neglected, the stator voltage impresses directly the stator flux in accordance with the equations (7) and (8).

$$V_s = \frac{d\psi_s}{dt} \quad (7)$$

$$d\psi_s = V_s dt \quad (8)$$

Therefore the variation of the stator flux space vector due to the application of the stator voltage vector  $V_s$  during a time interval of  $\Delta t$  can be approximated as in equation (9).

$$\Delta\psi_s = V_s \Delta t \quad (9)$$

### 3.2. Torque Control

$$T_e = \frac{3}{2} \frac{P}{2} \frac{L_m}{L_s} \psi_s \psi_r \sin \gamma \quad (10)$$

The electromagnetic torque given by equation (10) is a sinusoidal function of  $\gamma$ , the angle between  $\Psi_s$  and  $\Psi_r$  as shown in Fig.3. The variation of stator flux vector will produce a variation in the developed torque because of the variation of the angle  $\gamma$  between the two vectors as in equation (11).

$$\Delta T_e = \frac{3}{2} \frac{P}{2} \frac{L_m}{L_s} (\psi_s + \Delta\psi_s) \psi_r \sin \Delta\gamma \quad (11)$$

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 [3].

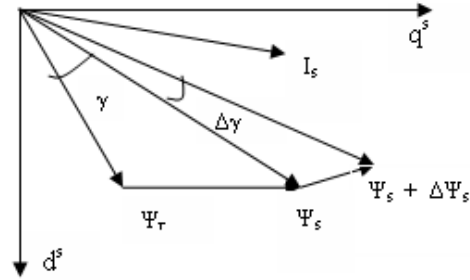


Fig. 3 Stator flux and rotor flux space vectors

## 4. Simulation Results

A direct torque control algorithm of Induction motor drive has been modelled and simulated using Matlab/Simulink simulation package [8], [9]. The simulink model of the three phase induction motor rated 10 HP, 415 V, 1440 rpm is shown in Fig.4. The motor is fed from an IGBT PWM inverter. The MATLAB / SIMULINK model for switching logic is developed and shown in Fig. 5. The transient performance of the developed DTC model has been tested by applying a variable load torque command on the mechanical dynamics. The flux reference is maintained at 0.9 Wb.

Figure 6 shows the results obtained. Figure 6 (a) and Fig. 6 (b) shows the electromagnetic torque and Fig 6 (c) shows the rotor speed of the machine. This demonstrates that the developed DTC achieved high dynamic performance in speed response to changes in demand torque. However, there is some performance degradation with torque overshoot in the torque transient owing to the hysteresis controllers used. Figure 6 (d) shows the d axis stator current. Figure 6 (e) shows the stator flux magnitude, emphasizing the decoupled action of torque and flux control. It is observed that the variation of motor torque does not influence fluxes. Figure 6(f) shows the stator current magnitude.

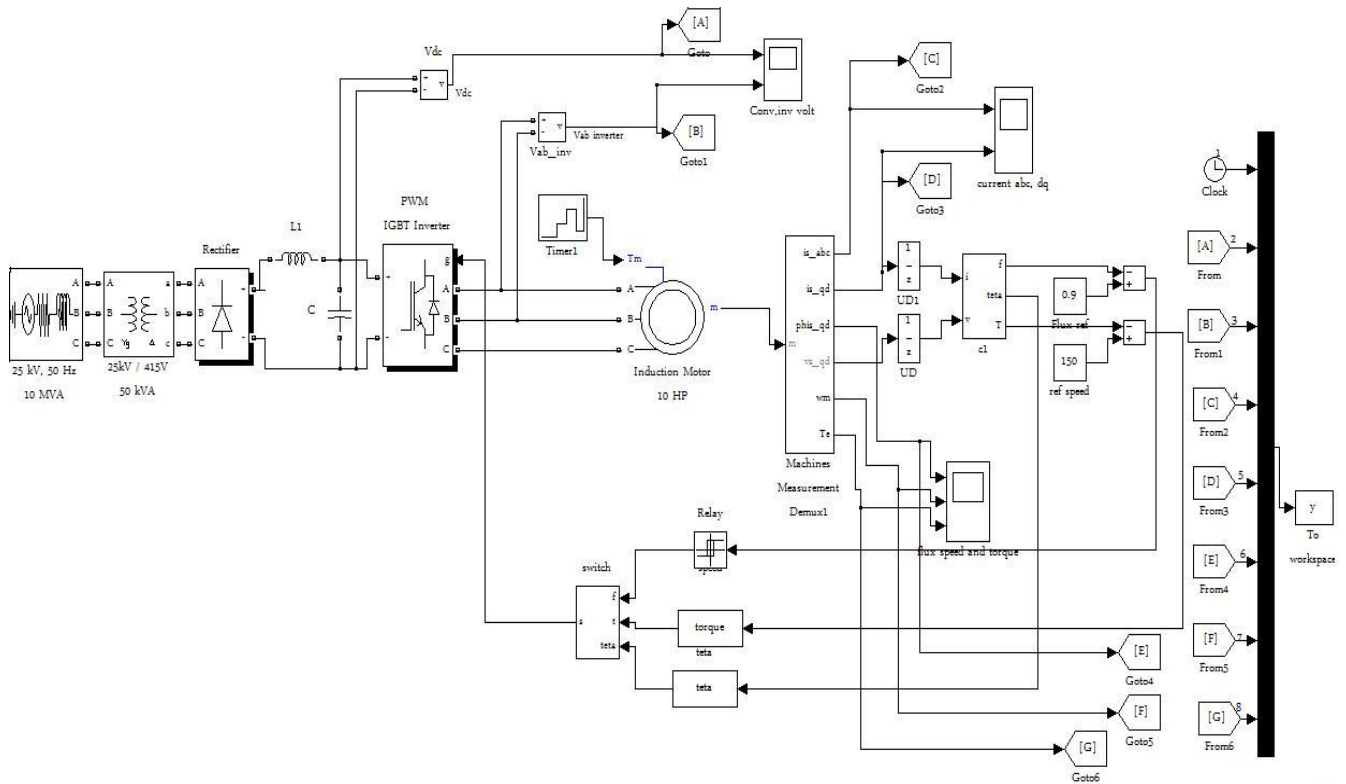


Fig. 4 MATLAB model for DTC scheme

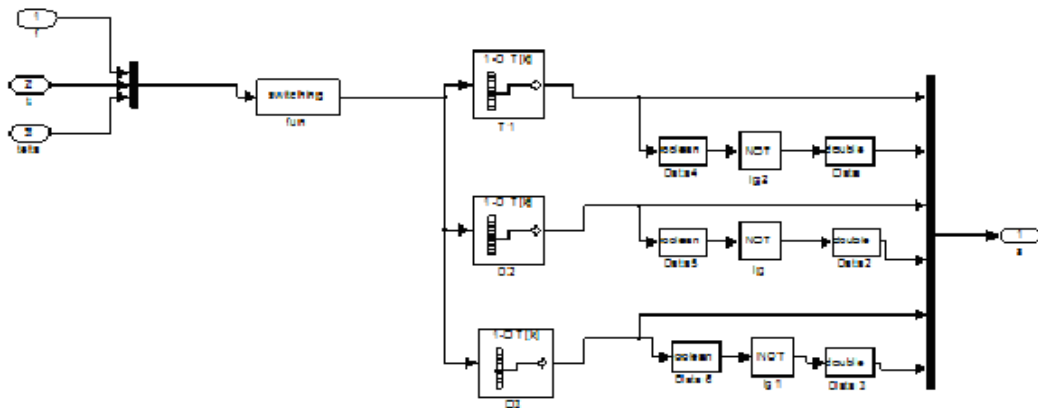


Fig. 5 Simulink model for switching logic of inverter

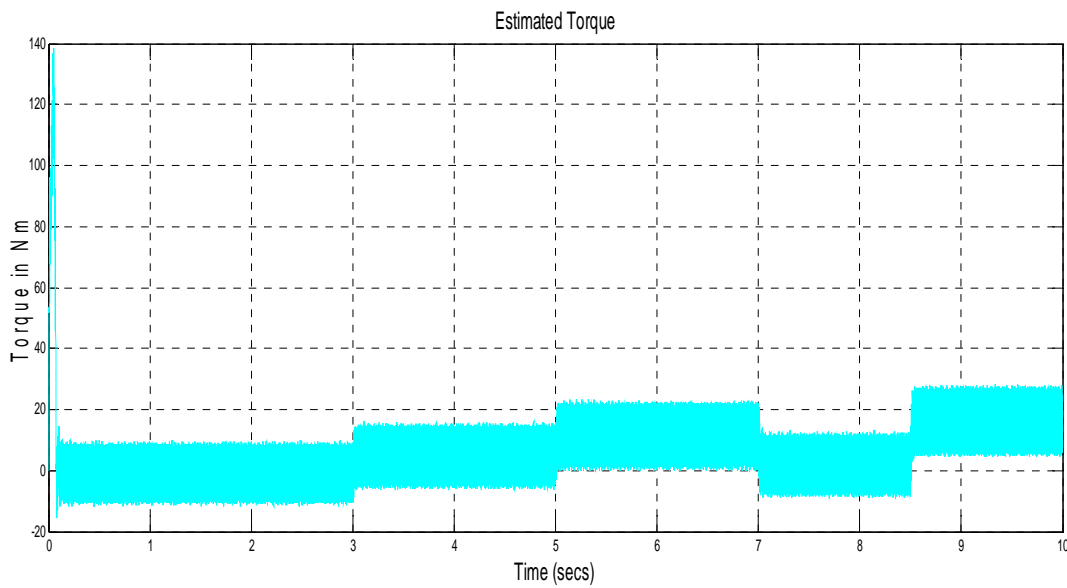


Fig.6 (a) Electromagnetic torque

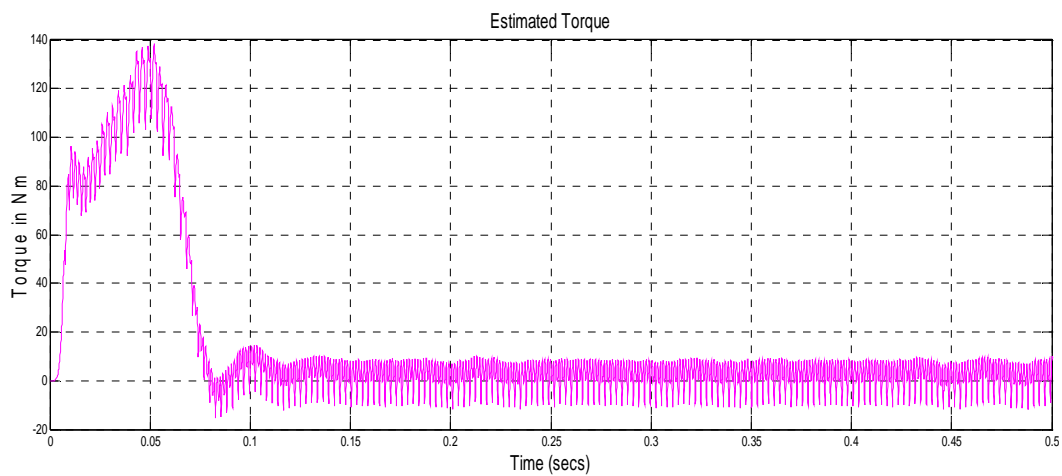


Fig. 6(b) Initial starting transients of estimated torque

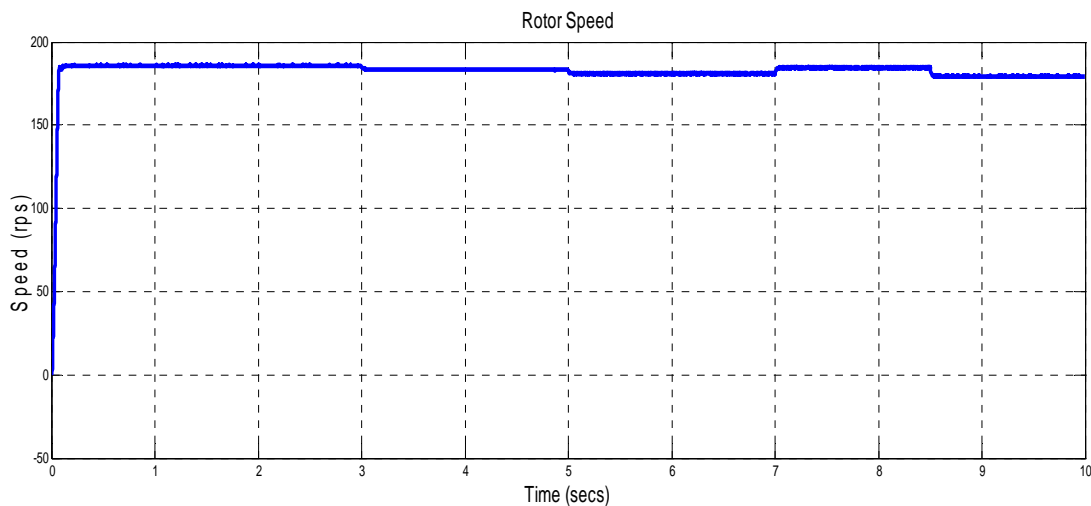


Fig. 6 (c) Rotor speed

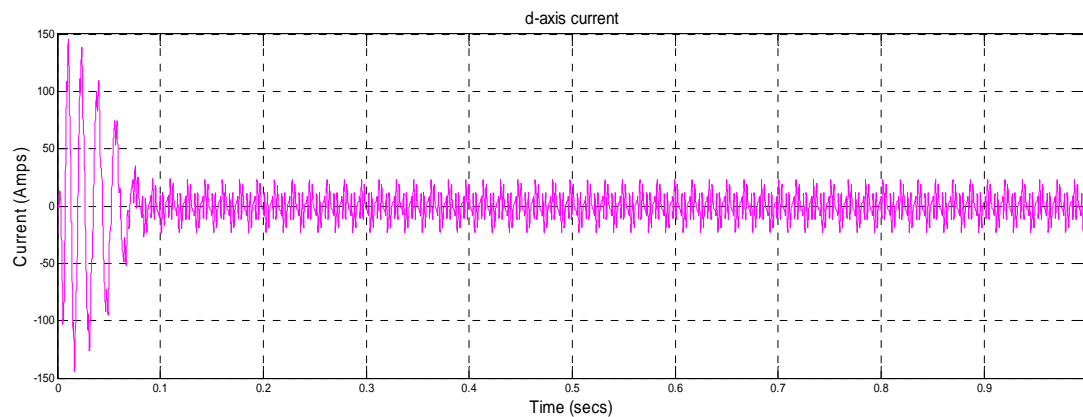


Fig. 6 (d) d axis stator current

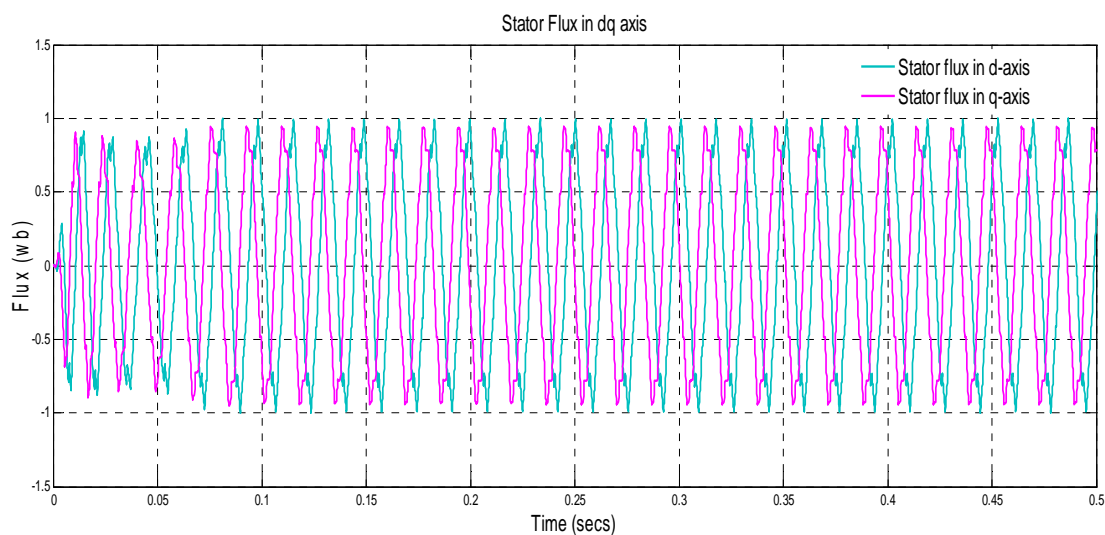


Fig. 6 (e) Stator flux magnitude

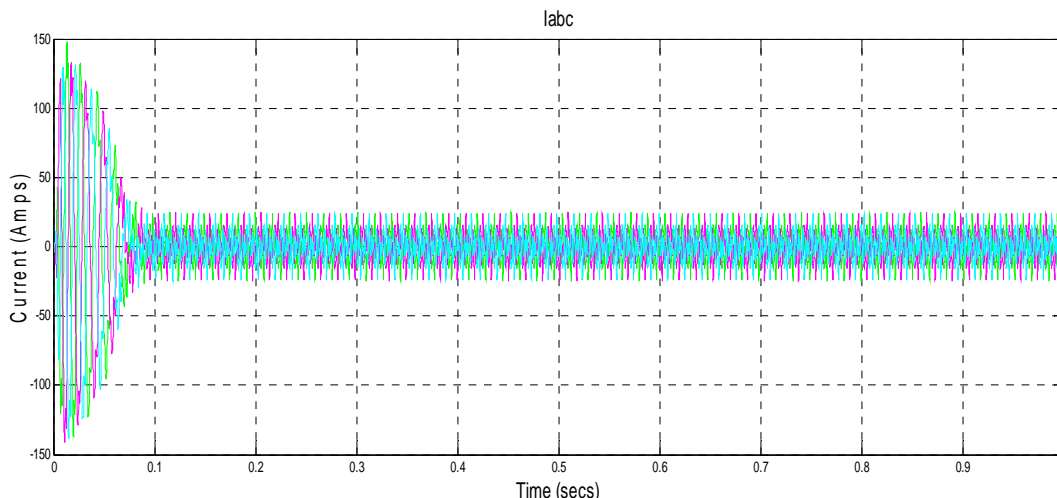


Fig. 6 (f) Stator current

## 5. Conclusions

The work carried out in this paper is aimed and focused to develop a Simulink model of direct torque control of 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 performed on a 10 HP induction machine fed by an IGBT PWM inverter. The feasibility and the 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. DTC represents a viable alternative to FOC, being also a general philosophy for controlling the ac drives in both motor and generator mode of operation. From a general perspective, FOC requires an accurate estimation of the rotor flux vector. However, when an accurate estimation of the motor flux is available, there is no need to set up a current control loop and DTC is the natural solution.

The main features of DTC can be summarized as follows.

- DTC operates with closed torque and flux loops but without current controllers.
- DTC needs stator flux and torque estimation and, therefore, is not sensitive to rotor parameters.
- DTC is inherently a motion-sensor less control method.

DTC has a simple and robust control structure; however, the performance of DTC strongly depends on the quality of the estimation of the actual stator flux and torque.

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