Design and Implementation of a Direct Torque Control Space Vector Modulated Three Phase Induction Motor Drive

Shrishell Muchande, Arvind Kadam, Keerthi Unni, and Sushil Thale

Fr. Conceicao Rodrigues Institute of Technology,
Vashi, Navi Mumbai, MH, India – 400703
shirish_muchande@rediffmail.com, arvind_hk@ymail.com,
keerthy101@yahoo.com, ssthale@gmail.com

Abstract. Electric motor drives find a wide range of applications ranging from very precise, position controlled drives used in the field of robotic applications to variable speed drives for industrial process control. By use of fast switching power electronic converters, the input power is processed and applied to the motor. With the recent developments in the area of power electronics and due to availability of low cost, high performance digital signal processors, the motor drives becomes an affordable entity for most of the industrial applications. In variable speed drive applications the dc machines have been replaced by ac drives. Many control techniques have been developed and used for induction motor drives namely the scalar control, vector or field- oriented control, direct torque and flux control, and adaptive control. Amongst them, the direct torque and flux control is found to be independent of the machine rotor parameters and offers the added advantage of eliminating the need for any speed or position sensors. The direct torque and flux control is also called direct torque control (DTC) and is an advanced scalar control technique. The basic DTC scheme eliminates the need for PI regulators, co-ordinate transformations, current regulators and PWM signal generators. Further, DTC offers a good torque control in steady state and transient operating conditions. This paper presents the details of the design and implementation of a direct torque controlled space vector modulated drive for an induction motor using Texas Instrument's Piccolo series TMS320F28069 digital signal controller.

Keywords: Induction motor, Scalar Control, Vector Control, Direct Torque Control, Flux estimators, PWM, Duty Cycle, transient response, Space Vectors, Voltage Source Inverter.

1 Introduction

Because of low cost, simple construction, high reliability and low maintenance, induction machine is widely used for industrial commercial and domestic applications The induction motor could be considered as a higher order non-linear system with a considerable complexity [1-2]. The speed of induction motor can be controlled by

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changing the pole, frequency or the stator voltage. With the use of power electronics, it is possible to vary the input frequency of a motor. This makes induction motor suitable for variable speed drives. The development of high power fast switching components like Insulated Gate Bipolar Transistor (IGBT) and MOSFETs and efficient control methods (using Digital Signal Processors DSPs) makes the control of induction motor easier and precise [3]. The control for high performance induction motor drives includes the scalar control and the vector control method.

In scalar control, instead of alignment in space, only the magnitude of the controlled variables like flux, current and voltage etc. are controlled. During the steady state conditions, scalar control improves the performance and efficiency of the machine whereas during transient condition, because of inherent coupling between the torque and flux, the response of machine is sluggish. The disadvantage of scalar control is that it gives a slow transient response. Vector control method controls magnitude as well as alignment of controlled variables. Generally the current is split up into torque producing component and the flux producing component. These two components are decoupled i.e. they are kept orthogonal to each other. Because of this, the change in torque command does not change the flux value. This improves the transient response of the motor. Vector control gives the high performance and more efficient control features. In vector control the system variables need to be transformed into d-q reference frame which rotates synchronously with the stator field. In synchronously rotating reference frame the stator currents appear as a dc which makes the analysis of control variables simpler [2].

The direct torque control of induction machines can be considered as an alternative to field oriented control of induction motors. Implementation of DTC needs a controller, torque & flux calculator and voltage sourced inverter (VSI) [2]. In DTC control, it is possible to achieve fast torque response, selection of optimal switching vector and direct and independent control of torque and flux. The harmonic losses can be reduced by reducing inverter switching frequency [4]. Recently, based on the traditional DTC method, a new control scheme called Direct Torque Control – Space Vector Modulated (DTC – SVM) has been developed. This eliminates the drawbacks of traditional DTC. This technique was claimed to have nearly comparable performance with vector controlled drives. Basically, the DTC-SVM strategies are the methods, which operate with constant switching frequency. Compared to the FOC scheme, DTC scheme is simple, eliminates the need for feedback current control and frame transformation, and gives a fast and good dynamic torque response [3]. Feedback signal processing in DTC is somewhat similar to stator flux-oriented vector control. Hysteresis-band control generates flux and torque ripple and switching frequency does not remain a constant. Stator flux vector and torque estimation is required, but the values are not sensitive to rotor parameters.

2 Literature Survey

R. Arunadevi el al. [5] has proposed the direct torque control of induction motor using Space Vector Modulation (SVM). The stator flux vector, and the torque produced by the motor, T_{em}, can be estimated using the following equations [5].

$$\bar{\lambda} = \int (\overline{V_S} - R_S \cdot \overline{I_S})\, dt \tag{1}$$

$$T_{em} = \frac{3}{2} \cdot \frac{P}{2} \left(\overline{\lambda_S} \times \overline{I_S}\right) \tag{2}$$

Once the current stator flux magnitude and output torque are known, the change required in order to reach the demanded values by the end of the current switching period can be determined. Over a short time period, the change in torque is related to the change in current, which can be obtained from the equation (3). The voltage $\overline{\mathrm{E}}$ can also be determined by using the stator flux and current vectors.

$$\Delta I_S = \frac{\bar{V} - \bar{E}}{L'_S} \Delta t \tag{3}$$

The change in torque can be obtained as

$$\Delta T_{em} = \frac{3}{2} \cdot \frac{P}{2} \cdot \frac{\Delta t}{L'_S} \left[\overline{\lambda_S} \times (\bar{V} - \bar{E})\right] \tag{4}$$

The change in the stator flux,

$$\Delta \lambda_S = (\bar{V} - R_S \cdot \overline{I_S}) \cdot \Delta t = \bar{V} \cdot \Delta t \tag{5}$$

The equations can be solved to find the smallest voltage vector, required to drive both the torque and flux to their reference values. The required stator voltage can be calculated by adding on the voltage drop across the stator resistance calculated using the current measured from the last cycle. The voltage required, to drive the error in the torque and flux to zero, is calculated directly. This calculated voltage is then produced using Space Vector Modulation. If the inverter is not capable of generating the required voltage then the appropriate voltage vector which will drive the torque and flux towards the reference value is chosen and held for the complete cycle.

To improve the performance of VSI fed DTC drive many modifications are suggested by various researchers [6-11]. Vinay Kumar and Srinivasa Rao [12] have proposed the new algorithm for direct torque & flux control of three phase induction motor based on the control of slip speed and decoupled between amplitude and angle of reference stator flux for determining required stator voltage vectors. The hysteresis comparators and voltage-switching table of conventional DTC gets eliminated here. But, the reference value of stator flux linkage needs to be known in advance. This method also requires calculation of the reference for voltage space vector and SVPWM technique to be done. In this technique, the torque control is achieved by maintaining the reference stator flux to be constant. The instantaneous electromagnetic torque is given by [12].

$$T_e(t) = \left[\frac{3}{2} \cdot P \cdot \frac{L_m^2}{R_r \cdot L_S^2} \cdot |\Psi_S^2|\right] \cdot \left[1 - e^{-e/\tau}\right] \cdot \left[\frac{\Delta}{\Delta t} \cdot \theta_{slip}\right] \tag{6}$$

The instantaneous electromagnetic torque control is performed by changing the value of slip angle which is controlled by using direct stator flux control method.

Dinkar Prasad et. al. [13] has developed a low cost hardware prototype which is capable of giving higher PWM switching frequency. The DTC scheme is implemented without using sector calculator and switching table formulation, which is the unique feature of this scheme. Gdaim et al. [14] have proposed two intelligent approaches to improve the direct torque control of induction machine; fuzzy logic control and artificial neural networks control.

In conventional direct torque control (CDTC), the switching frequency is variable which depends on the mechanical speed, stator flux, stator voltage and the hysteresis band of the comparator. The distortion in torque and current is due to sector changes. Several solutions have been proposed to keep constant switching frequency. Ahmed. A. Mahfouz et. al. [1] has proposed a new modified DTC with a space vector modulator (SVM), and fuzzy logic controller (FLC). The SVM and FLC are used to obtain constant switching frequency and decoupling between torque and flux respectively. The two hysteresis controllers are replaced with FLC and the look-up table replaced by space vector modulator (SVM). The FLC block based on are torque error e_T, flux error e_F, and the stator flux position information gives space voltage vector V_S^* and its position angle θ_v at the output. Based on the output of FLC, SVM block generates constant frequency pulses to trigger the inverter. Space vector modulated direct torque control using field programmable gate array (FPGA) is presented in [15]. To get the desired load angle, the stator flux Ψs is changed by selecting proper stator voltage vector (V_S).

3 Problem Definition

The operation of the conventional DTC is very simple but it produces high ripple in torque due to considered non-linear hysteresis controllers. The sampling frequency of conventional DTC is not constant and also only one voltage space vector is applied for the entire sampling period. Hence the motor torque may exceed the upper/lower torque limit even if the error is small. The problems usually associated with DTC drives which are based on hysteresis comparators are [16-17]:

1. Because of the use of hysteresis operations the switching frequency is variable.
2. Due to inherent inaccuracy in stator flux estimations, the drive performance can get severely degraded.
3. During start up and at low speed values, there is the difficulty in controlling the startup current and there exists inaccuracies in the calculation of currents due to motor parameter variation.

The objective of this research work is to attempt the implementation of Direct Torque Control (DTC) of Induction Motor (IM) with sinusoidal PWM (SPWM). The implementation consists of designing the hardware setup for DTC based induction motor drive using DSP. The motor of rating 0.37 KW has been selected. The algorithm and programming required for DTC has to be implemented through the DSP. The main aim of the research work includes running a motor with an inverter using PWM module of the DSC, sensing the current and speed values from the motor on real time basis, calculation of torque and flux values through the DSC and establishing closed loop control of the motor speed by comparison with the reference values. The sensing of the current and voltage must happen on real time basis so that the torque and the flux calculations remain accurate. Also, the reference frame transformations followed by the integrations and the comparisons should be performed at each and every sample which requires a controller which can do computations extensively. Hence the digital signal controller from Texas Instruments TMS320F28069 is used instead of a microcontroller, as it can do mathematical calculations promptly.

4 Analysis of DTC – SVM

The flux linkage equations in terms of the currents are [16]:

$$\Psi_{qs}^{e} = L_{ls} \cdot I_{qs}^{e} + L_m \cdot \left(I_{qs}^{e} + I_{qr}^{e}\right) \tag{7}$$

$$\Psi_{ds}^{e} = L_{ls} \cdot I_{ds}^{e} + L_m \cdot (I_{ds}^{e} + I_{dr}^{e}) \tag{8}$$

$$\Psi_{qr}^{e} = L_{lr} \cdot I_{qr}^{e} + L_m \cdot \left(I_{qs}^{e} + I_{qr}^{e}\right) \tag{9}$$

$$\Psi_{dr}^{e} = L_{lr} \cdot I_{dr}^{e} + L_m \cdot (I_{ds}^{e} + I_{dr}^{e}) \tag{10}$$

The torque equations of induction motor are given by [16]:

$$T_e - T_l = J \cdot \frac{d}{dt} \cdot \omega_r \tag{11}$$

$$T_e = \left(\frac{3}{2}\right) \cdot \frac{P}{2} \cdot \left(\Psi_{sd}^{e} \cdot I_{sq}^{e} - \Psi_{sq}^{e} \cdot I_{sd}^{e}\right) \tag{12}$$

where, T_l is load torque, ω_r is electrical speed. The torque equation with the corresponding variables in stationary frame:

$$T_e = \left(\frac{3}{2}\right) \cdot \frac{P}{2} \cdot \left(\Psi_{ds}^{s} \cdot I_{qs}^{s} - \Psi_{qs}^{s} \cdot I_{ds}^{s}\right) \tag{13}$$

Consider a three phase two level voltage source inverter where E is the dc link voltage, and $S_a^+, S_b^+ and\ S_c^+$ are the states of the upper switches. The load is a balanced induction motor; the phase voltages generated by the voltage source inverter and applied to the stator are constrained by [16]:

$$V_{as} + V_{bs} + V_{cs} = 0 \tag{14}$$

Where, V_{as}, V_{bs}, V_{cs} are the phase voltages of inverter. The phase voltages in terms of S_a, S_b, S_c can be expressed as [2]:

$$V_{as} = \frac{2S_a - S_b - S_c}{3} E \tag{15}$$

$$V_{bs} = \frac{S_a + 2S_b - S_c}{3} E \tag{16}$$

$$V_{cs} = \frac{-S_a - S_b + 2S_c}{3} E \tag{17}$$

$$\overline{V_S^S} = \frac{2}{3} \cdot E \cdot \left[S_a + S_b \cdot e^{j2\pi/3} + S_c \cdot e^{j4\pi/3}\right] \tag{18}$$

Equation (18) represents the space vector of phase voltages generated by the PWM inverter. Taking the 8 values $\overline{V_k}\ (k = 0\ to\ 7)$ the space vectors with, $(k = 1\ to\ 6)$, have the same amplitude $(2E/3)$ and phase angles equal to$[(k-1) \cdot \pi/3]$. Remaining two vectors $(k = 0\ \&\ 7)$ coincides with the zero space vectors.

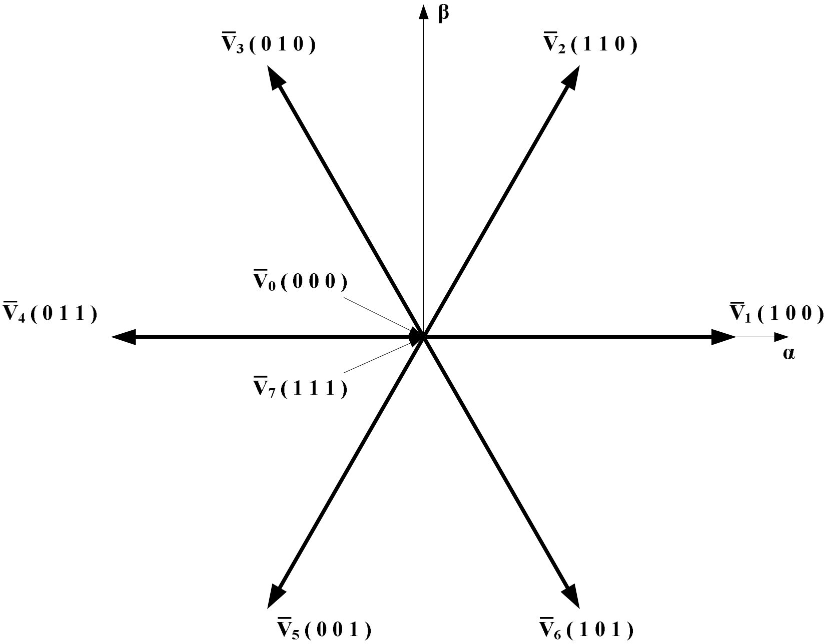


Fig. 1. Inverter output voltage phase vectors [2]

The inverter output voltage phase vectors are shown in Fig 1. The space vector modulations technique differs from the conventional sine PWM methods. There are no separate modulators used for each of the three phases. Instead of them, the reference voltages are given by space voltage vector and the output voltages of the inverter are considered as space vectors. There are eight possible output voltage vectors, six active vectors $\overline{V_1}\ to\ \overline{V_6}$, and two zero vectors $\overline{V_0}$& $\overline{V_7}$ (Fig.2). The reference voltage vector is realized by the sequential switching of active and zero vectors.

$$V_S^* \cdot T_S = V_0 \cdot T_0 + V_1 \cdot T_1 + V_2 \cdot T_2 + V_7 \cdot T_7 \tag{19}$$

$$T_S = T_0 + T_1 + T_2 + T_7 \tag{20}$$

Where, V_S^* is the desired space vector, T_S is the switching time, $T_0, T_1, T_2$and T_7 are the time intervals, and V_1, V_2 are the vectors adjacent to V_S^*.

In the Fig. 2, the reference voltage vector V_s^* and eight voltage vectors, which correspond to the possible states of inverter, are shown. The six active vectors divide a plane for the six sectors I - VI. In the each sector the reference voltage vector V_s^* is obtained by switching on, two adjacent vectors for appropriate time. As shown in Fig.2, the reference vector V_s^* can be obtained by the switching vectors of V_1, V_2 and zero vectorsV_0, V_7.

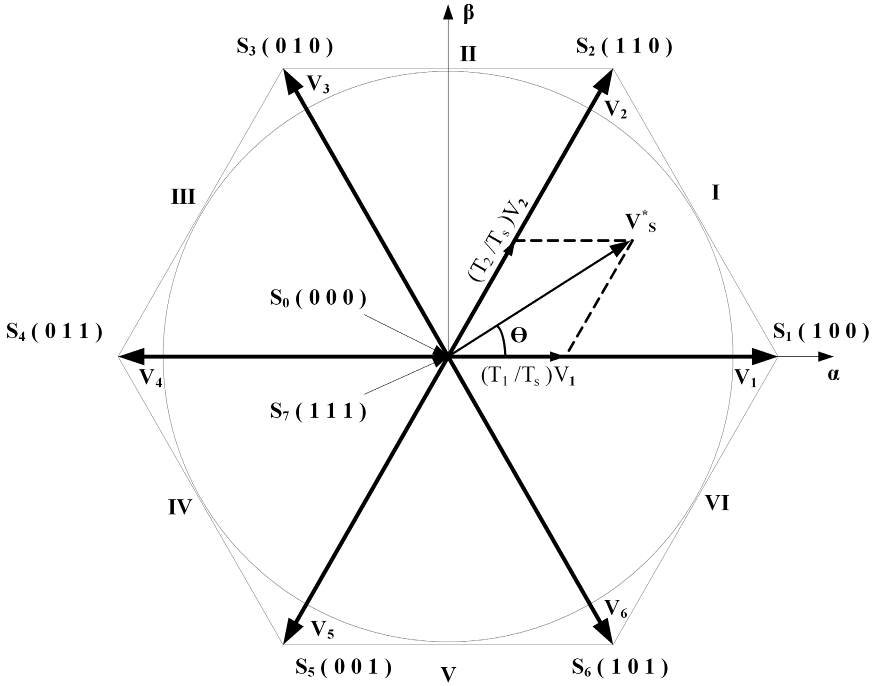


Fig. 2. States of the inverters using SVM control

5 Hardware Implementation

The IM drive based on DTC-SVM control structure can be operated in scalar control mode. The system configuration is shown in Fig. 3.

Initially, the torque and the flux values are estimated from the voltage and current values that are sensed. The torque and the flux values are then compared with the reference values. There are two hysteresis controllers implemented in software; one for the torque and another for the flux. The controller outputs are used to select the appropriate voltage vectors using Space Vector Modulation. The PWM signals are generated according to the voltage vectors and this controls the inverter output. The inverter then makes the motor to remain in the designed speed.

The hardware implementation of the system includes the design of three phase inverter with the gate driver circuit, design of voltage and current sensing circuit, the design of PCB artwork of the same. The conventional topology of a three leg inverter is selected for implementation. The nameplate details of the induction motor are given in Table 1.

The operational switching frequency for induction motor drive is typically selected between 2 kHz to 20 kHz depending upon the power rating of the motor. Here the switching frequency selected is 10 kHz.

$$\text{DC Link voltage, } V_{dc} = \sqrt{2} \times V_{LL} = 311\,V$$

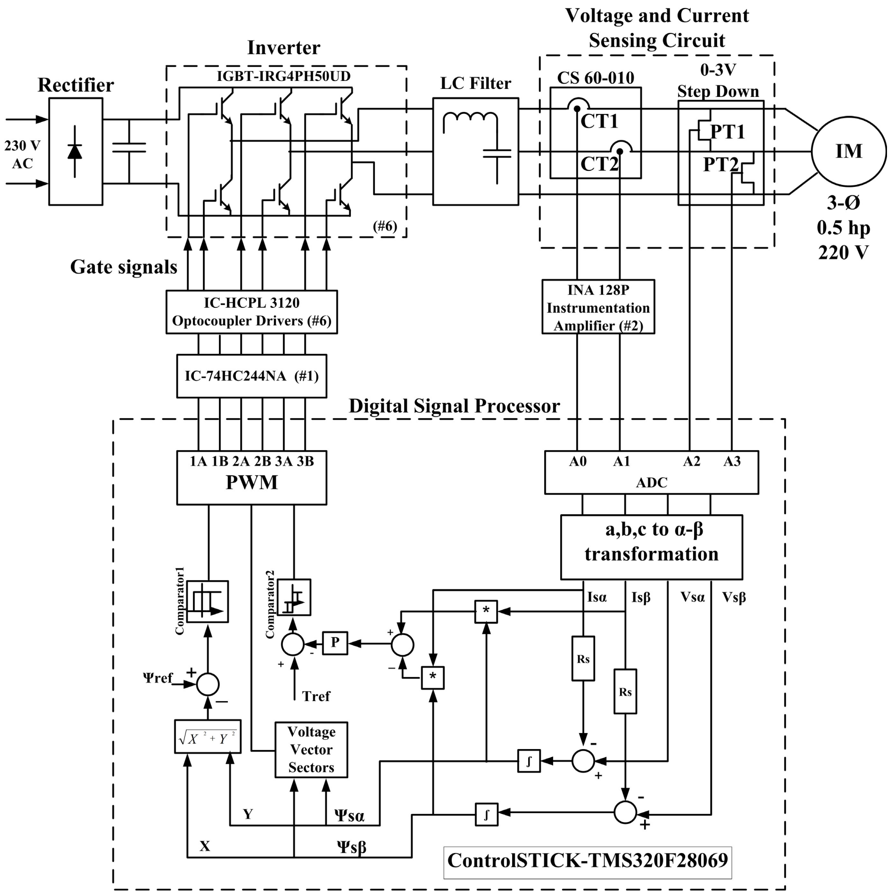


Fig. 3. Block diagram of implemented control algorithm [4]

Table 1. Specifications of Induction Motor

Type of Motor	3 Φ 50Hz Squirrel Cage Induction Motor
Rating in hp/kW	0.5 hp/0.37 kW
Voltage Rating	220 Volts Line to Line
Full Load Line Current / pf	1.05 Amps / 0.74
Full Load Efficiency	74%
Starting Current (Full voltage)	3.6 Amps
Full Load Torque	0.26 Nm
Stator Resistance (R_s)	10.9 Ω
Stator Self Inductance L_s	0.125 H
Nominal Speed	1440 rpm

The current rating of the device selected to be at least 10 times of the nominal current requirement of the motor at operating temperature of 70°C and 10 kHz switching frequency i.e. 10A. The net power capacity of the inverter is calculated as below,

$$Power\ rating\ of\ inverter = \frac{Power\ rating\ of\ motor}{(Effi.of\ motor\ \times Effi.of\ the\ inverter)}$$

Assuming efficiency of inverter as 85 %, the power rating of the inverter is calculated as,

$$= \frac{370\ W}{(0.74 \times 0.85)}$$

$$= 588\ W$$

The gate driver selected is IC HCPL-3120 suitable to drive the IGBT IRG4PH50UD. The required isolated power supplies for the gate driver ICs is derived from 230/15V transformer with eight windings, out of which six are rated for 200mA continuous current rating and two for 1 Amps. The six power supplies are used for inverter and two for auxiliary circuits like level shifter, amplifiers in sensing board. The buffer IC 74HC244NA is used as the interface between the DSP controller and gate driver. The detailed list of components selected for 3Ø inverter and the specifications of the designed systems are listed in Table 2 and Table 3 respectively.

Table 2. Component Selection for 3Φ Inverter

Sr. No	Component	Type
1.	Switches	IGBT-IRG4PH50UD
2.	Gate Driver	HCPL3120
3.	Buffer	74HC244NA
4.	Regulator	LM 7815
5.	Fuse	2A
6.	Rectifier	DB107

Table 3. System Specifications

Sr. No.	Parameters	Specifications
1.	Power capacity	600W
2.	Operating Voltage and frequency	3Φ, 220V,50Hz
3.	DC link Capacitor	700µF/900V
4.	Inverter switching frequency	10kHz
5.	Filter Inductance	6mH
6.	Filter Capacitors (3 in delta and 3 in star connection)	50µf /440V ac each

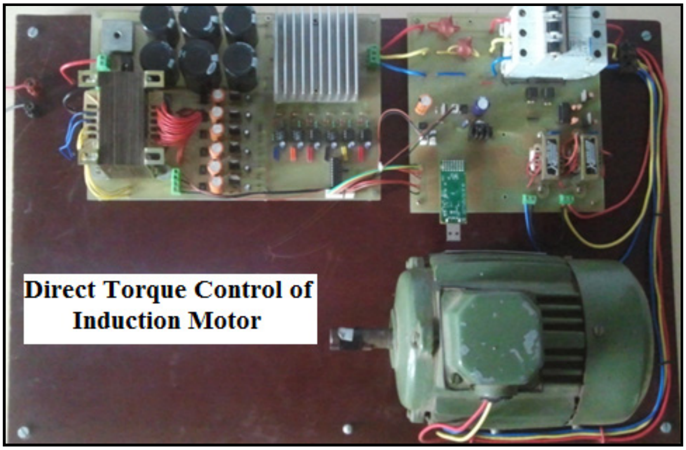


Fig. 4. Laboratory setup (a) without step up transformer

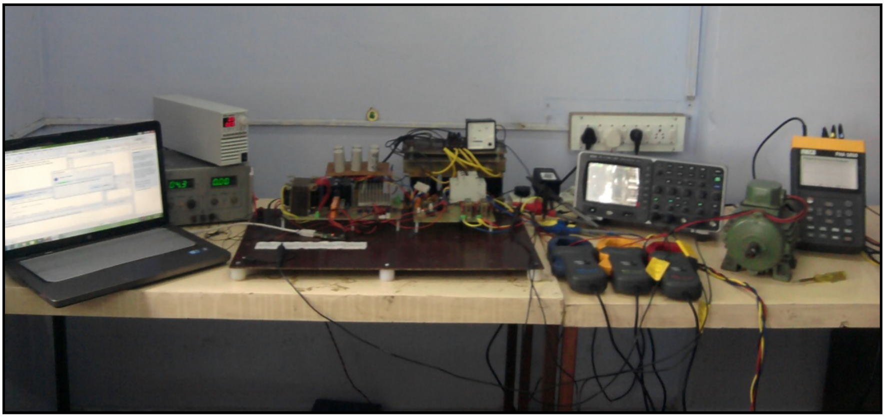
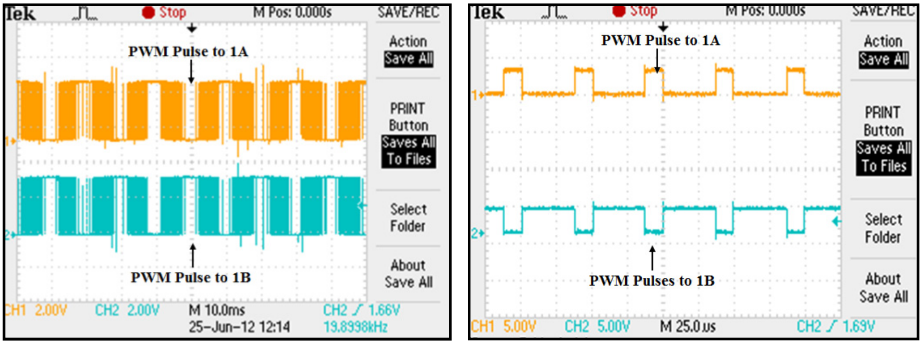


Fig. 5. Laboratory setup (b) with step up transformer and filter and measuring equipments

The hardware set up shown in Fig. 4 and Fig. 5 consists of a Voltage Source inverter (VSI) and 0.37kW induction motor. The induction motor is fed by the VSI through an MCB mounted on the sensing board. The two current sensors, CS60-010 (Coil craft), and two PTs (step-down transformer) are used to sense the currents and voltages. DTC control algorithm is implemented in the drive based on DSP controller TMS320F28069.

6 Hardware Results

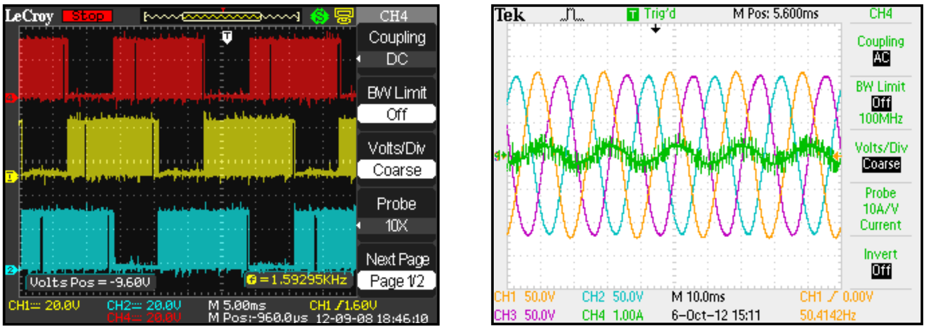
The ePWM module of the DSC generates complimentary pulses for inverter with appropriate dead band. The dead band of 0.5 µSec each at both falling and rising edge of PWM is selected. This is done by assigning the dead band registers, a value calculated as per the clock setting of TMS320F28069. Fig. 6 shows the complementary PWM pulses for upper and lower switch of first leg of inverter.



(a) (b)

Fig. 6. (a) PWM pulse of 1A& 1B at a frequency of 10 KHz and (b) Expanded view

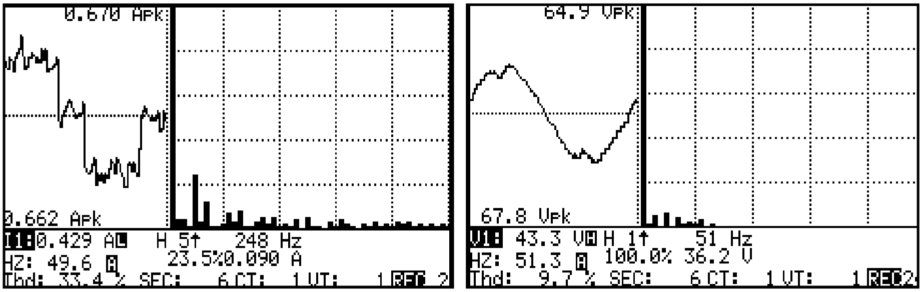
The current sensors produce an output voltage, between 10mV to 100mV, proportional to the actual currents flowing in the system. The current sensor output is directed to an instrumentation amplifier INA129 to amplify it to the suitable level. The DTC-SVM algorithm is implemented in Code Compose Studio (CCS-4) platform. The PWM pulses generated using SVM and the motor terminal voltages are as shown in the Fig 7.



(a) (b)

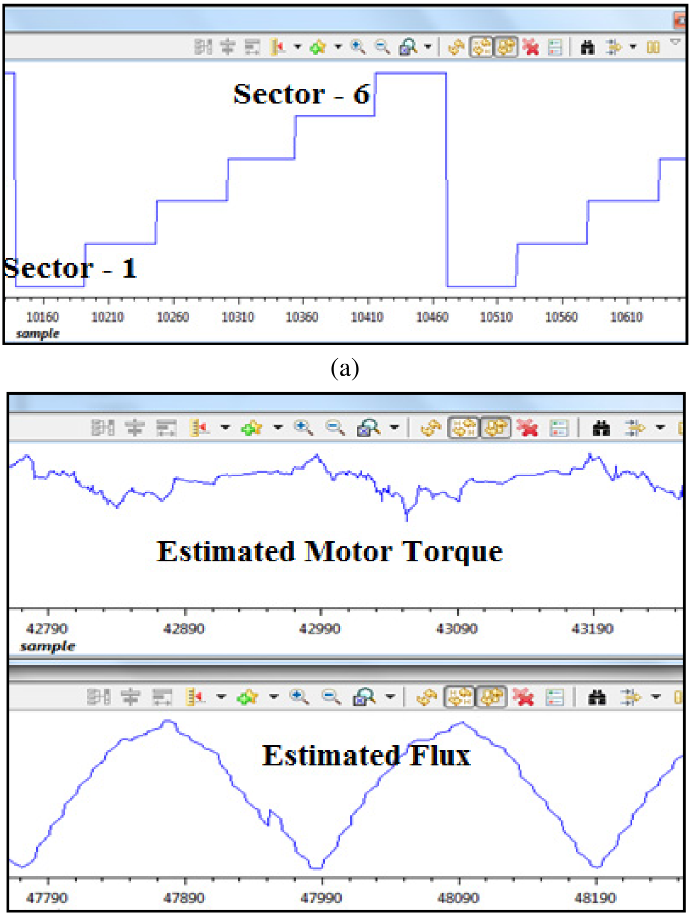
Fig. 7. (a) Space Vector Modulated PWM gate pulses for inverter (b)Motor's 3 phase output terminal voltages and current after filtering

Fig. 8 shows the motor current and terminal voltages measured using Power analyzer. The test was carried out with low DC link voltage. The test was conducted to verify the THD contents in the output. The current harmonics show the significant amplitude at 5th and 7th harmonics compared to the rest. The harmonic spectrum of voltage shows the dominance of 3rd and 5th harmonics produced by the energizing component of transformer used for boosting the voltage.



(a) (b)

Fig. 8. Induction motor phase A terminal voltage and line current waveforms recorded by Meco's Power and Harmonic Analyzer PHA5850



(a)

(b)

Fig. 9. Screen shot of CCS-4 platform indicating (a) sector selection of space vector modulation (b) torque and flux estimation based on measurement of actual motor terminal voltages and currents

Fig. 9 shows the screen shot of CCS-4 indicating the SVM implementation, where the reference voltage vector position is identified in terms of sector which repetitively moves from 1 to 6 and repeats. The position of the reference vector is generated using torque error and flux error generated in DTC algorithm. The reference torque is given as input to the system in the form of predefined variable set to a particular value. The estimation of flux and torque is done at the sampling rate of 60μsec through an timer interrupt and interrupt service routine (ISR), allows accommodation of fast dynamic response to torque changes in DTC.

7 Conclusion and Future Scope

Amongst all the control methods for induction motor drives, direct torque and flux control method provides a simplified, dynamically fast and machine rotor parameters independent control. It also eliminates the use of any speed or position sensors, reducing the cost of the system. The basic DTC scheme which is characterized by the absence of PI regulators, co-ordinate transformations, current regulators and PWM signals generators, makes it possible to use lower end processors to be used for control further reducing the cost of the drive. The DTC allows a good torque control in steady state and transient operating conditions to be obtained. The modification of basic DTC to accommodate features like accuracy of control, reduction in torque jitter, speed control loop and lesser dependency on accurate measurement of motor voltages and currents, various researchers proposed the modified form of DTC. This caused an increase in complexity of implementation of DTC, but retained most of the inherent features of DTC intact. As the complete hardware is ready for an induction motor drive, the work can be extended to implement following features;

- Reduction in torque ripple by means of reducing the torque error band which will require accurate and noise free measurement of current and voltages.
- Reduction of torque ripple through modification of control strategy with introduction of suitable torque and flux controller

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