DSP BASED IMPLEMENTATION OF FIELD ORIENTED CONTROL OF THREE-PHASE INDUCTION MOTOR DRIVES

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Abstract

The objective of this paper is to presents a practical implementation of field oriented control of three-phase induction motor based on Space Vector Pulse Width Modulation technique using Digital Signal Processing (DSP) board TMS320F2812. The control algorithm for the drive application is built with Code Composer Studio version 3.1. The motor control is divided into two control loops; inner current loop and outer speed control loop using PI controller. The rotor flux quantities are estimated using computational rotor time constant, rotor angular velocity and stator current. As a feedback of field oriented control, an incremental encoder is attached at the motor shaft and a Hall effect current sensor is used to detect the sent current to the motor. The performance of the drives system is tested under different speed command and load disturbances

***Index Terms:** digital signal processor, field oriented control, induction motor, Space Vector Pulse Width Modulation*

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1. INTRODUCTION

Induction motors are widely used in industrial application due to their relatively low cost, high reliability and almost free maintenance. The induction motor applications are very wide spread from centrifugal pump, compressor, punching presses, elevator and many more [1]. It is rugged, lower cost and weight, reliable and almost free maintenance when compared to DC motor. The control of induction in variety of speed range become possible with solid state inverter and power supply in variable frequency and voltage. The high performance modern electrical drive must have the following characteristics; fast transient response and small overshoot, small steady state error, robust to parameter variation and uncertainties of the system, wide range operation, direct and fail-safe control algorithm and inexpensive implementation and maintenance free operation [2].

In high performance drive systems, in which control variables include the torque developed in the motor, vector control (field orientation) technique are necessary [3]. Basic concept of field orientation that introduced by Hasse in 1969 and Blaschke in 1972, constitutes the most important paradigm in the theory and practice of induction motor. The concept showed that decoupled control of flux and torque was theoretically possible in three-phase AC machine, thus emulate the concept of controlling separately exited DC motor.

However, this field oriented control strategies are extremely complex and the analogue or the mixed analogue-to digital scheme has some disadvantages such as the complication of the circuit, poor consistency and zero drift [4]. Then, by using a high-performance digital signal processor, it can be represented in all-digital field control system and becomes a popular research on digital control for ac drives [4-6]. With digital signal processing board, TMS320F2812 [7] is a specifically designed for 32-bit fixed-point DSP chip for motor control. It has advantages such high speed 150MIPS performance, 2 set of 12 outputs Pulse Width Modulation (PWM), 2 set of 4 inputs Quadrature Encoder Pulse (QEP) input and 16 channels 12-bit analogue to digital (A/D) converter.

Pulse width modulation is a technique to generate pulses with a certain rules and goals through supplying DC voltage for inverter to obtain variable speed drive operations. It has been shown that Space Vector Pulse Width Modulation (SVPWM) generates less harmonic distortion in the output voltage and currents, provides more efficient use of DC supply voltage when compared to sinusoidal modulation technique [8, 9]. It is possibly the best among all the PWM techniques for variable speed drive application[10]. The aim of this paper is to present a practical implementation of field oriented control based on SVPWM technique in digital signal processor to control three-phase induction motor. The dynamic response of speed, stator q-axis current reference and phase 'a' stator current reference are analyzed with different speed reference load disturbances. It shows that excellent behaviour is verified in most cases.

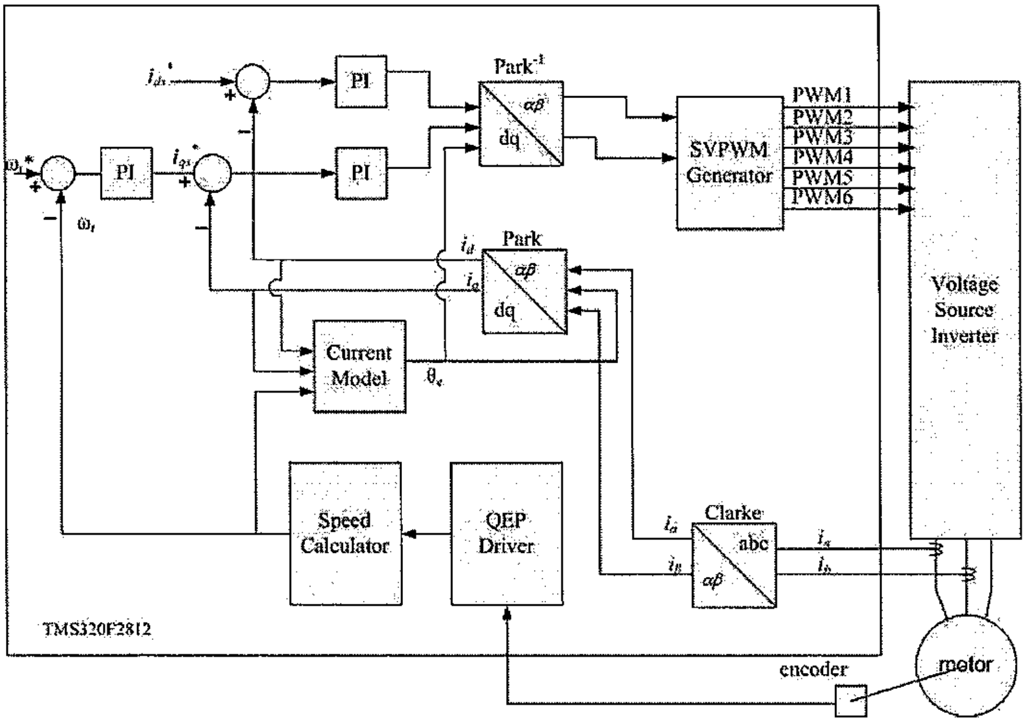

Figure 1: Overall block diagram for indirect field oriented controlled of induction motor drives using TMS320F2812 DSP

2. FIELD ORIENTED CONTROL OF THREE-PHASE INDUCTION MOTOR

Three phase squirrel cage induction motor in synchronously rotating reference frame can be represent in mathematical form [10] as (1)-(8):

$$V_{qs} = R_s i_{qs} + \frac{d\varphi_{qs}}{dt} + \omega_e \varphi_{ds} \quad (1)$$

$$V_{ds} = R_s i_{ds} + \frac{d\varphi_{ds}}{dt} - \omega_e \varphi_{qs} \quad (2)$$

$$V_{qr} = R_r i_{qr} + \frac{d\varphi_{qr}}{dt} + (\omega_e - \omega_r)\varphi_{dr} \quad (3)$$

$$V_{dr} = R_r i_{dr} + \frac{d\varphi_{dr}}{dt} + (\omega_e - \omega_r)\varphi_{qr} \quad (4)$$

Where $V_{qr}, V_{dr} = 0$, and the flux equation:

$$\varphi_{qs} = L_{Ls} i_{qs} + L_m (i_{qs} + i_{qr}) \quad (5)$$

$$\varphi_{qr} = L_{lr} i_{qr} + L_m (i_{qs} + i_{qr}) \quad (6)$$

$$\varphi_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) \quad (7)$$

$$\varphi_{dr} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr}) \quad (8)$$

Where Vqs, Vds are the applied voltages to the stator, ids, iqs, idr, iqr are the corresponding d and q axis stator current and rotor currents. φqs, φqr, φds, φdr, are the stator and rotor flux component, Rs, Rr are the stator and rotor resistances, Lls, Llr denotes stator and rotor inductances, whereas Lm is the mutual inductance. The electromagnetic torque equation is:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(\varphi_{dr} i_{qs} - \varphi_{qr} i_{ds}) \quad (9)$$

Where P, denote the pole number of the motor. If the vector control is fulfilled, the q-axis component of the rotor field φqr would be zero. Then the electromagnetic torque is controlled only by q-axis stator current and becomes:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(\varphi_{dr} i_{qs}) \quad (10)$$

Figure 1 shows the block of indirect field oriented controlled of induction motor drives. The control is divided into two control loops; inner current loop and outer speed control loop. The rotor flux quantities are estimate using computational rotor time constant, rotor angular velocity and stator current as in (11).

$$\frac{d\theta_e}{dt} = \frac{1}{Tr}\frac{i_{qs}}{i_{ds}} + \omega_r \qquad (11)$$

The rotor speed ωr is compared to rotor speed command ωr* and the resulting error is processed in the PI speed controller. The PI speed controller will generate stator q-axis current reference iqs*. Both reference current in d-axis and q-axis is compared to the feedback from the motor current through Clark and Park Transformation. From the respective error the voltage command signal is generated through PI controller and converted to two phase voltage through Inverse Park Transformation and fed to SVPWM which generates switching signal for Voltage Source Inverter (VSI). These in turn, control the stator winding current of induction motor, so controlling the speed of the motor. The transformation between stationary a-b-c frame, stationary α-β frame and synchronously rotating d-q frame are describes as the following equation [10].

- Clarke; convert stationary a-b-c frame to stationary α-β frame.

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & \frac{-1}{3} & \frac{-1}{3} \\ 0 & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \qquad (12)$$

- Clarke^{-1}; convert stationary α-β frame to stationary a-b-c frame.

$$\begin{bmatrix} I_a \\ I_b \\ I_b \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \qquad (13)$$

- Park; convert stationary α-β frame to rotating d-q frame.

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \qquad (14)$$

- Park^{-1}; convert rotating d-q frame to stationary α-β frame.

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta_e & -\sin\theta_e \\ \sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} \qquad (15)$$

3. SPACE VECTOR PULSE WIDTH MODULATION TECHNIQUE

Space vector pulse width modulation refers to special switching sequence of the upper three device of three-phase voltage source inverter. This special switching technique for the power device results in three pseudo-sinusoidal currents in the stator phase. As shown in Figure 2, when an upper transistor is switched on, (S1, S3, S5 is 1) the corresponding lower transistor is switched off (S2, S4, S6 is 0). Therefore, the on and off states of the upper transistors S1, S3, S5 can be used to determine the output voltage. The relationship between the switching variable vector [a, b, c]t and the line-to-line voltage vector [Vab,Vbc,Vca]t and phase voltage vector [Va Vb Vc]t are given by (16)-(17).

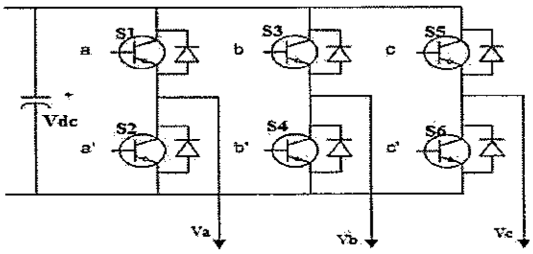

Figure 2. Three-phase voltage source inverter

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \qquad (16)$$

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \qquad (17)$$

The three-phase bridge inverter has 23 permissible switching states. Six nonzero vectors (V1 – V6) shape the axes of a hexagonal as depicted in Figure 3, and feed electric power to the motor. The angle between any adjacent two non-zero vectors is 60 degrees. Meanwhile, two zero vectors (V0 and V7) are at the origin and apply zero voltage to the load. The eight vectors are called the basic space vectors and are denoted by V0, V1, V2, V3, V4, V5, V6 and V7. The Vref is the phase to centre voltage which is obtained by proper selection of adjacent vectors V1 and V2 [11].

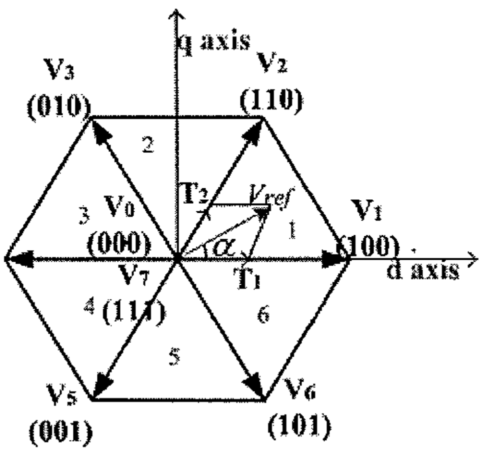

Figure 3. Voltage Vector and Reference Vector

4. HARDWARE SETUP

Figure 4 shows the experimental setup of the drives system. The hardware configuration for this work can be depicted in Figure 5. The control and drives board is consist of DSP TMS320F2812 and Digital Motor Control DMC1500 from Texas Instrument and auxiliary circuit, Hall effect current sensor and interface of encoder input. The computer is the host during debugging the program and connected to DSP using parallel port. The Code Composer Studio (CCS) version 3.1 is used to translate field oriented control in "C" language or assembly language code for DSP controller. The DSP is generating six pulse width modulation (PWM) signals by means of space vector PWM for six power switching devices in the inverter. Two input currents of the induction motor, ia and ib are measured using current sensor and rotor speed was monitored using an encoder. Then, the data are sent to the DSP board via analogue-to-digital converters.

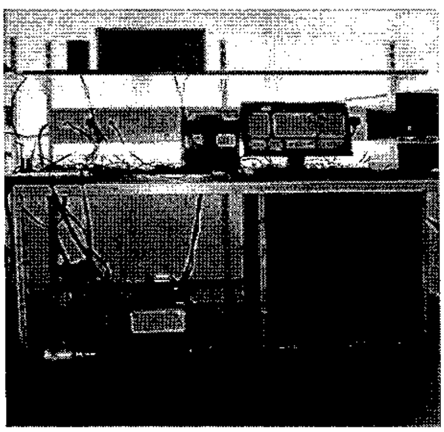

Figure 4. The experimental setup

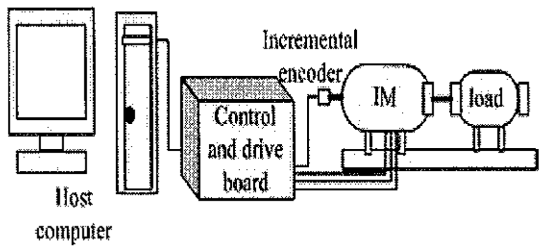

Figure 5. Hardware configuration

The induction motor use for this experiment is 1.5KW, 1400rpm. The parameter of the motor are, Rs=4.6 Ω Rr=5.66, Ls=0.3153H, Lr=0.3153H and Lm=0.3H. The stator q-axis current reference is limit to 5A. The encoder type is incremental optical encoder 500 pulses per revolution. The load is give using hysteresis current brake from Magtrol Inc. DC voltage is limited to 380V, the maximum value of the Digital Motor Control DMC1500 can achieve, which means that the rated speed is reduced to 900 rpm. It should be noted that using higher dc voltage will result in a higher rate of change of torque. The PI speed control is designed so that the system can tolerate with load disturbances with less than 15 percent overshoot. The control system parameters are: Kpw=7.5, Kiw=0.001, Kpq=0.08, Kiq=0.001, Kpd=2.0, and Kid=0.15. The voltage source inverter switching frequency is constant, fs=20 kHz.

5. EXPERIMENTAL RESULT

The first experiment is to run the motor from standstill in different speed command. Three speed commands is considered, which are 900rpm, 600rpm and 450rpm.

Figure 6 shows the response of the speed command and its associate stator phase 'a' current and stator q-axis current reference. From the figure, good tracking performance is achieved, the rotor speed track the speed command with small overshoot. Acceleration under no-load condition is extremely rapid even for rated speed command. At initial state, the current signal presents a high value because it is require a high torque to increase the motor speed. When steady state occurs, the motor torque has only to compensate the frictions, so the current is low. As for motor torque, it has high at initial and operates in the current limit given 5 A (when speed at acceleration zone) and decreases in a constant region when steady state is achieved. The second experiments is to observe the performance of the motor when the speed is changes from initial 450 rpm and then increased to 900 rpm and vice versa. The speed, stator q-axis current reference and stator phase current reference is presented in

Figure 7

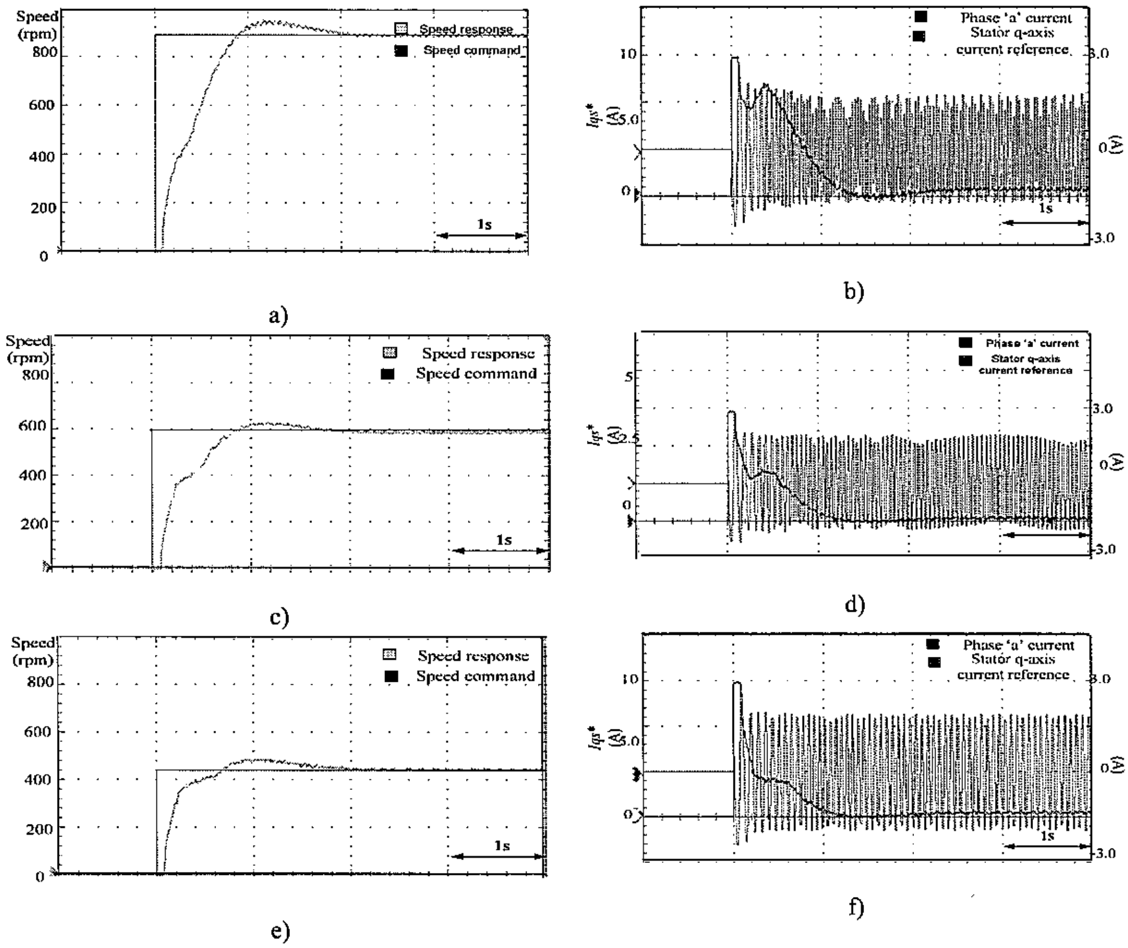

Figure 6 Experimental result; speed response, stator phase 'a' current reference and stator q-axis current reference (a)-(b) 900rpm,(c)-(d) 600rpm, (e)-(f) 450rpm

Overshoot and undershoot appears when the speed is increased and decreased. However the system can recover to the speed demand less than two second. When the speed is increased from 450rpm to 900rpm, the q-axis stator current has a constant value in the initial state, then increases to its maximum limit due to acceleration of the motor, and finally remains constant again. When the speed is decrease from 900rpm to 450rpm, the q-axis stator current has a constant value in initial state, and then decreases to its minimum limit due to deceleration of the motor. The third experiment is to investigate the transient of the drive when load 2.5Nm is applied to the motor from standstill for speed 900rpm and 450rpm. From Figure 9, the speed tracking performance is same with no-load condition. As for stator q-axis current reference, it has high at initial and operates in the current limit given 5A in acceleration mode and decrease to constant region significantly higher than no-load condition, to compensate the load given to the motor. The stator current phase 'a' is significantly increased in the transient, compared to no-load operation, and remain constant with slightly higher compared to no-load condition when actual speed approaches the speed command

The last experiment is to test the robustness of the system and investigate the load rejection behaviour when load is applied to the motor at steady state operation.
Figure9 shows the performance of the speed response during 750rpm, when 2.5Nm, 5Nm, 7.5Nm and rated load, 9Nm is applied to the motor. Slight oscillation occurs when load is applied and significantly affected when rated load, 9Nm is applied. It may be observed that the motor can recover less than 2.0 seconds. The stator phase 'a' current reference is significantly increased as the load applied is increased and the q-axis stator current, it has high value at initial when load is applied and operates in different constant region depending on

the load applied when actual speed approaches the speed command

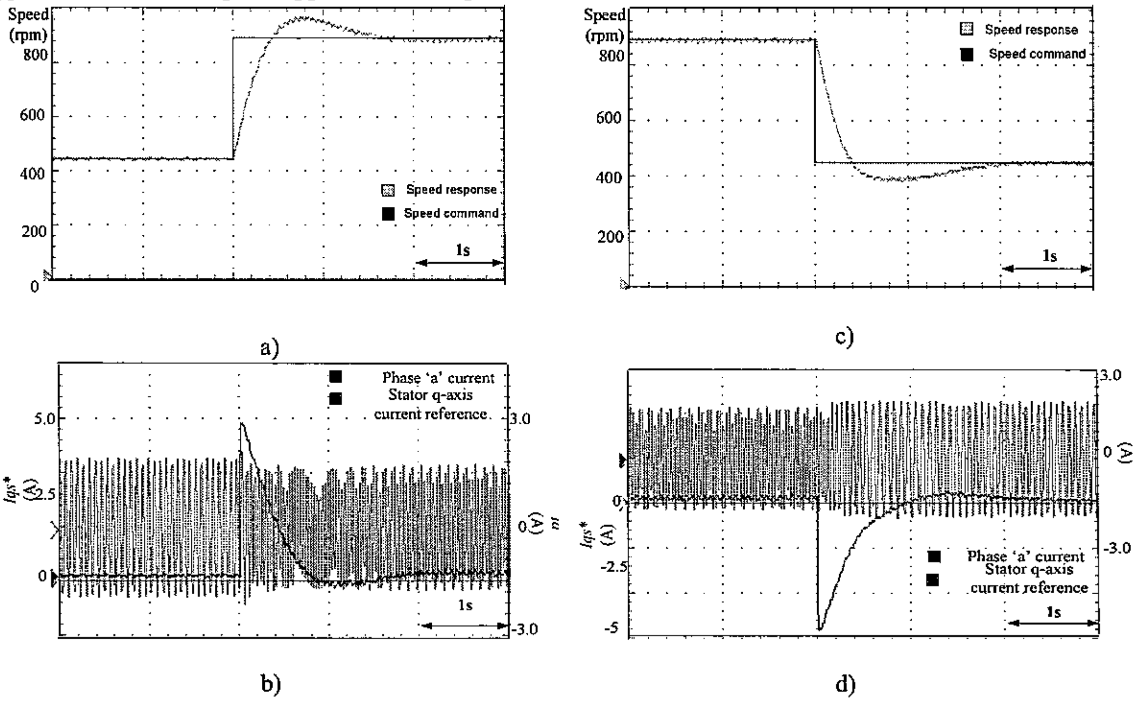

Figure 7. Experimental result; speed responses, stator phase 'a' current reference and stator q-axis current reference. (a)-(b): speed increase from 450rpm to 900rpm. (c)-(d): speed decrease from 900rpm to 450rpm

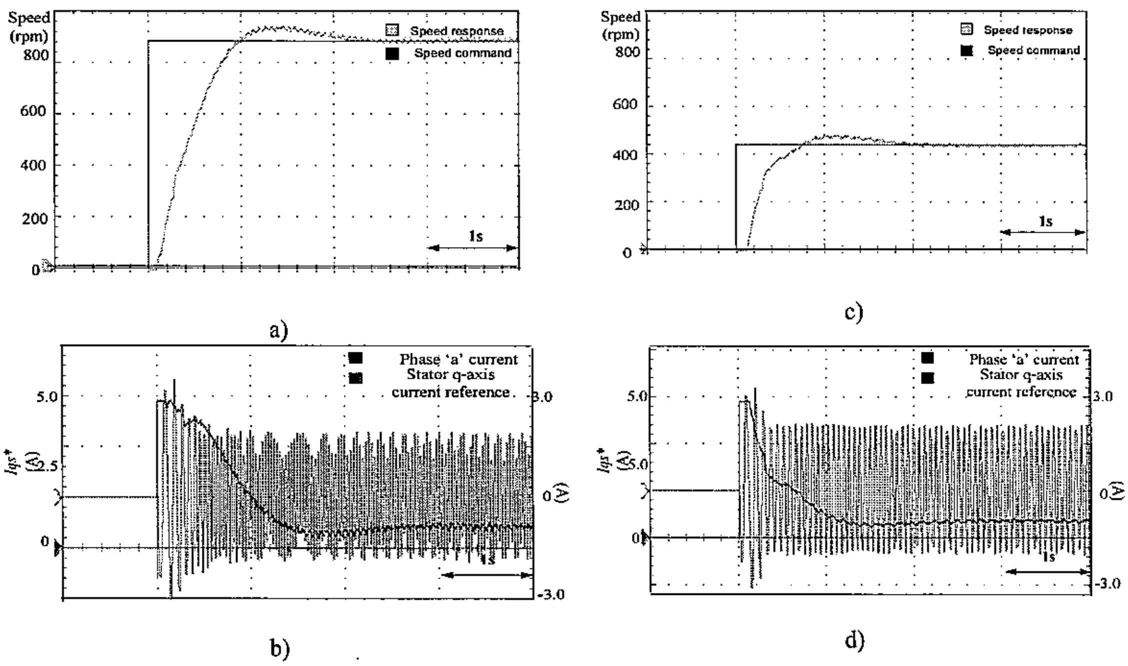

Figure8. Experimental result, speed responses speed responses, stator phase 'a' current reference and stator q-axis current reference, when loaded 2.5Nm from initial (a)-(b) 900rpm, (c)-(d) 450rpm

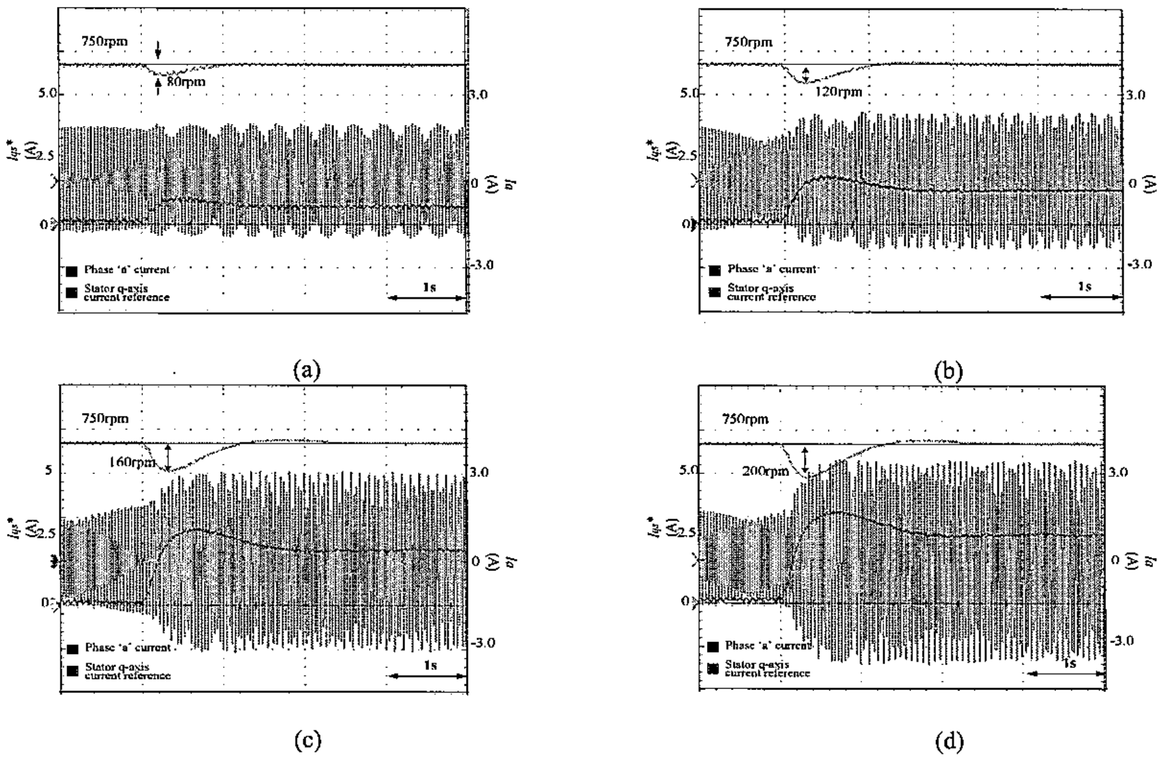

Figure9. Experimental result, speed responses, stator phase 'a' current reference and stator q-axis current reference at 750rpm when load is applied (a) 2.5Nm, (b) 5Nm (c) 7.5Nm (d) 9Nm

CONCLUSIONS

The DSP implementation for field oriented control which integrated Space Vector Pulse Width Modulation technique of three-phase induction motor was successfully developed. From the experimental result, the motor can operate in different speed command and also different load disturbance with the same PI controller setting. The results from this practical experiment can be taken into consideration when comparing with other types of advanced controller. The success in creating programs for the entire algorithm in the DSP is a good move to make an advanced control schemes such as fuzzy control or sliding mode control.

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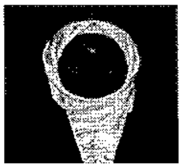
BIOGRAPHIES

Marizan bin Sulaiman was born in April 16, 1962 in Kuala Besut, Terengganu. He received the Bachelor of Science in Electrical Engineering in May 1984, the Master of Science in Electrical Engineering in December 1985, and Doctor of Philosophy in Electrical Engineering in May 1989 from the University of Missouri-Columbia. He is a registered member of the Board of Engineers, Malaysia (BEM) and the Institution of Engineers, Malaysia (IEM). He is Professor Electrical Engineering and has been appointed as Dean of Faculty of Electrical Engineering, the Dean of Centre for the Graduate Studies and the Assistant Vice Chancellor for Student Affairs and Alumni in UTeM. At present, the research interests include Electrical Power System and Control Engineering.



Fizatul Aini Patakor was born in Selangor, Malaysia in 1978. She received the degree in electrical engineering (power electrical) from Universiti Sains Malaysia, in 2001 and Msc Occupational Safety and Health from Universiti Utara Malaysia in 2008. She is a lecturer at Politeknik Sultan Abdul Halim Muadzam Shah. Currently, she is a PhD research student of Universiti Teknikal Malaysia Melaka. Her interest includes safety and health in engineering education, power electronic and drives control system.

Zulkifilie Bin Ibrahim was born in January 7, 1966 in Singapore. He received the B.Eng. (Electrical Engineering) from UTM - Malaysia in 1989. He received the Ph.D (Power Electronics & Control), Liverpool John Moores University in 1999. He has been assistant Professor and appointed as Dean of Faculty of Electrical Engineering, UTeM. At now, he focuses on Power Electronics, Electric Motor Drives, Fuzzy Logic, and Embedded Control Design & Application