ISSN 1827-6660
Vol. 2 N. 3
May - June 2007

International Review of Electrical Engineering (IREE)

Contents:

Security Assessment of Power Systems Using Contingencies Ranked by QV Modal Aggregated Participation Factors 293
by M. A. Ríos, H. Amaranto

Multi Objectives Optimization of the Active/Reactive/Environmental Dispatch of an Electrical Network 301
by S. Brini, H. Ben Aribia, H. Hadj Abdallah, A. Ouali

Wind Generator Output Power Smoothing by Using Pitch Controller 310
by S. M. Muyeen, M. H. Ali, R. Takahashi, T. Murata, J. Tamura

Analysis and Two-Dimensional Modelling of the Doping Effect on the Leakage Current in Polysilicon Transistors 322
by Y. Bourezig, B. Bouabdallah, B. Benichou, F. Gaffiot

Enhanced Micro Modeling Technique for Semiconductor Devices to Study Faulty Mode in Power Converters 327
by F. Charfi, M. B. Messaoud, B. François, K. Al-Haddad, F. Sellami

Shunt Active Power Filters and PWM Rectifiers in Three-Phase Three Wire Systems: a Survey 337
by E. Bárcenas, V. Cárdenas, J. Arau

Voltage-Source Active Power Filter with a Current Sensorless Control 346
by M. Routimo, M. Salo, H. Tuusa

A New Topology of Three-Phase Five Level Inverter Applied to Static VAR Generation Schemes 359
by T. H. Abdelhamid, N. H. Abbasy

Discrete Adaptive Speed Sensorless Drive of Induction Motors 369
by A. Oualha, M. Ben Messaoud

Comparative Study of Nonlinear Speed Observers for Induction Motors 378
by M. A. Gallegos-Lara, R. Alvarez-Salas, C. A. Nuñez-Gutierrez

Sensorless Control of a Linearized Induction Motor Drive 386
by K. B. Mohanty

Speed Sensorless Vector Control of Induction Motors Using Singularly Perturbed Sliding Mode Observer 398
by A. Mezouar, M. K. Fellah, S. Hadjeri

Three Phase Induction Motor Incipient Rotor's Faults Detection Based on Improved Root-MUSIC Approach 406
by A. H. Boudinar, A. Bendiabdellah, N. Benouzza, N. Boughanmi

(continued on outside back cover)

Praise Worthy Prize

(continued from outside front cover)

Design, Modelling and Control of a Linear Induction Motor 414
by M. A. Nasr Khoidja, B. Ben Salah

Exact Analytical Model of the No-Load Flux Density in the Air-gap, the Permanent Magnets and the Rotor Yoke for the Surface Mounted Permanent Magnet Motors 425
by F. Dubas, C. Espanet

High Performance Torque Control of Brushless DC Motor Drive Based on TMS320LF2407 DSP Controller 438
by A. Vahedi, H. Moghbeli, A. Halvaei Niasar

Incorporation of Vector Preisach Hysteresis Model in Transient Finite Element Analysis for a SMPM 448
by A. Mansouri, H. Trabelsi

Digital Step Motor Drive with EKF Estimation of Speed and Rotor Position 455
by M. Bendjedia, Y. Aït-Amirat, B. Walther, A. Berthon

Numerical Simulation of Seawater Flow Produced by Conduction MHD Pump 466
by N. Bennecib, S. Drid, R. Abdessemed

PWP
Praise Worthy Prize

€ 40,00

1827-6660 (200705/06)2:3;1-P

International Review of Electrical Engineering (I.R.E.E.), Vol. 2, N. 3
May – June 2007

High Performance Torque Control of Brushless DC Motor Drive Based on TMS320LF2407 DSP Controller

A. Vahedi[1], H. Moghbeli[2], A. Halvaei Niasar[3]

Abstract – *Brushless DC (BLDC) motor is attracting much interest due to its high efficiency, good performance and ease of control for many applications. This paper presents the design and implementation of a torque controller for a Brushless DC motor drive using the TMS320LF2407A digital signal processor (DSP) produced by Texas Instruments. Firstly, a theoretical analysis of a BLDC motor drive is presented and the validity of the proposed analysis is verified by simulation. The torque is controlled via current regulation directly. Then, hardware and software details of the system are explored. Finally, an experimental system included by a BLDC motor, DSP control board, inverters, rectifier is set up to validate the theoretical ones.* **Copyright © 2007 Praise Worthy Prize S.r.l. - All rights reserved.**

Keywords: *Brushless DC Motor, TMS320LF2407A DSP, Torque Control*

Nomenclature

B	Damping
e_a	Back-EMF voltage of phase A
e_b	Back- emf voltage of phase B
e_c	Back- emf voltage of phase C
E	Magnitude of phase back- emf voltage
i_a	Current of phase A
i_b	Current of phase B
i_c	Current of phase C
i_{dc}	DC-link current
i_{ref}	DC-link reference current
J	Moment inertia
K_e	Back-EMF voltage constant
K_t	Torque constant
L	Phase inductance
M	Mutual inductance
R	Phase resistance
T_e	Electromagnetic torque
T_a	Developed electromagnetic torque of phase A
T_b	Developed electromagnetic torque of phase B
T_c	Developed electromagnetic torque of phase C
T_L	Load torque
T_{Ref}	Torque reference
v_a	Terminal voltage of phase A
v_b	Terminal voltage of phase B
v_c	Terminal voltage of phase C
v_{dc}	DC-link voltage
ω_r	Rotor speed
SF1_x	Switching function of phase x (x=a,b,c)

I. Introduction

Recent development in permanent magnet (PM) materials, power electronics, fast digital signal processors (DSPs) and modern control technologies have significantly influenced the wide spread use of permanent magnet brushless (PMBL) motor drives in order to meet the competitive worldwide market demands of devices, products and processors. The availability of smart power electronics devices and their optimal topologies has accelerated the growth of cost effective and reliable inverter systems. Software controlled on-line implementation of optimal controllers has advanced the art of digital control of PMBL motor drives [1].

Motor drives are traditionally designed with relatively inexpensive analog components.

The weakness of analog systems is their susceptibility to temperature variations and component aging.

Another drawback is the difficulty of upgrading these systems.

Digital control structures eliminate drifts and, by using a programmable processor, the upgrades can be easily accomplished by software. The high performance of digital signal processors (DSPs) allows them to perform high resolution control and minimize control loop delays. These efficient controls make it possible to reduce torque ripple, harmonics and improve dynamic behavior in all speed ranges.

Manuscript received and revised May 2007, accepted June 2007

Overall, these improvements result in a reduction of system cost and better reliability [2].

High efficiency due to reduced losses, low maintenance and low rotor inertia of PM brushless motors have increased the demand of these motors in high performance applications such as aerospace, transportations and robotics.

PM brushless motors are categorized into two groups: sinusoidal flux waveform named PMSM or BLAC and trapezoidal flux waveform named brushless DC (BLDC).

Brushless DC (BLDC) motor with trapezoidal flux utilizes the trapezoidal back-EMF with square wave currents to generate constant torque.

It enjoys some advantages rather than BLAC motor as followings: higher torque for same motor density, lower and simpler manufacturing cost, Simple controller, very simple and cheap position sensors for commutations (3 Hall Effect sensors). The BLDC motor is inherently electronically controlled and requires rotor position information for proper commutation of currents [3]-[4].

On the other hand, DSP chips become popular for research on digital control for AC drives due to their high-speed performance, simple circuitry, and on-chip peripherals of a micro-controller into a single chip solution.

Especially the new generation DSP controller TMS320LF2407A produced by Texas Instrument, which has the advantages of high speed (MIPS) performance, 2 set (12 outputs) of PWM output, 2 set of QEP (Quadrature Encoder Pulse) input, 16 channels 10-bit A/D converter bits, General Purpose Input/Output, (GPIO), is very suitable to develop a fully digital controller and a complicated intelligent control algorithm in servo motor drives [5].

This paper presents the modeling and hardware implementation of BLDC motor drive. The basic analysis of BLDC motor drive is described. The drive system implementation and major part of control is realized through software.

II. Analysis of Brushless DC Motor Drive

II.1. Modeling of Three-Phase BLDC Motor

BLDC motor has characteristics as like as a DC motor, whereas it is controlled the same as AC motors. Fig. 1 shows the three phase currents waveforms with the trapezoidal back-EMF voltages of a BLDC motor [6].

As shown, to generate constant output torque, BLDC motor needs quasi square current waveforms, which are synchronized with the back-EMF. The typical mathematical model of a three-phase BLDC motor is described by the following equations:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \times \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

The electromagnetic torque is expressed as:

$$T_e = \frac{1}{\omega_m}\left(T_a + T_b + T_c\right) \quad (2)$$

which the developed electromagnetic torque of each phase is obtained by:

$$T_a = e_a i_a,\ T_b = e_b i_b,\ T_c = e_c i_c \quad (3)$$

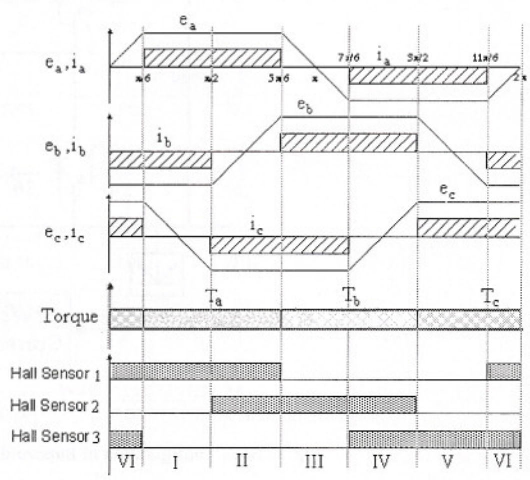


Fig. 1. Signal waveforms of a BLDC motor

The interaction of T_e with the load torque determines how the motor speed builds up:

$$T_e = T_L + J\frac{d\omega_r}{dt} + B\omega_r \quad (4)$$

The magnitude of back-EMF voltage (E) depends on the speed and is calculated from:

$$E = K_e \omega_r \quad (5)$$

Brushless DC motor is controlled as easy as a separate-exited DC motor. Reference current is related to desired torque as:

$$T_{Ref} = K_t I_{ref} \quad (6)$$

It means that the electromagnetic torque is controlled by regulating the DC-link current.

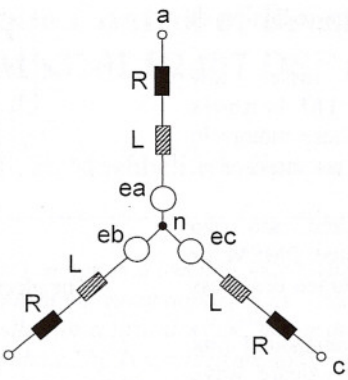


Fig. 2. Equivalent circuit of the three- phase BLDC motor

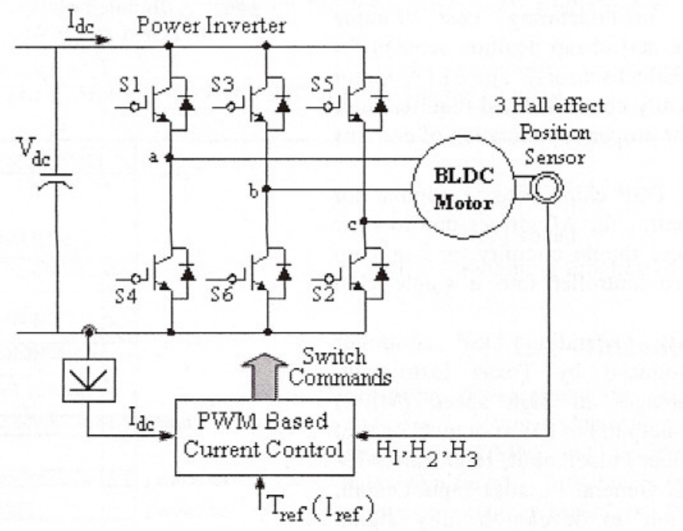


Fig. 3. Basic configuration of trapezoidal BLDC motor drives with DC-link current controlled

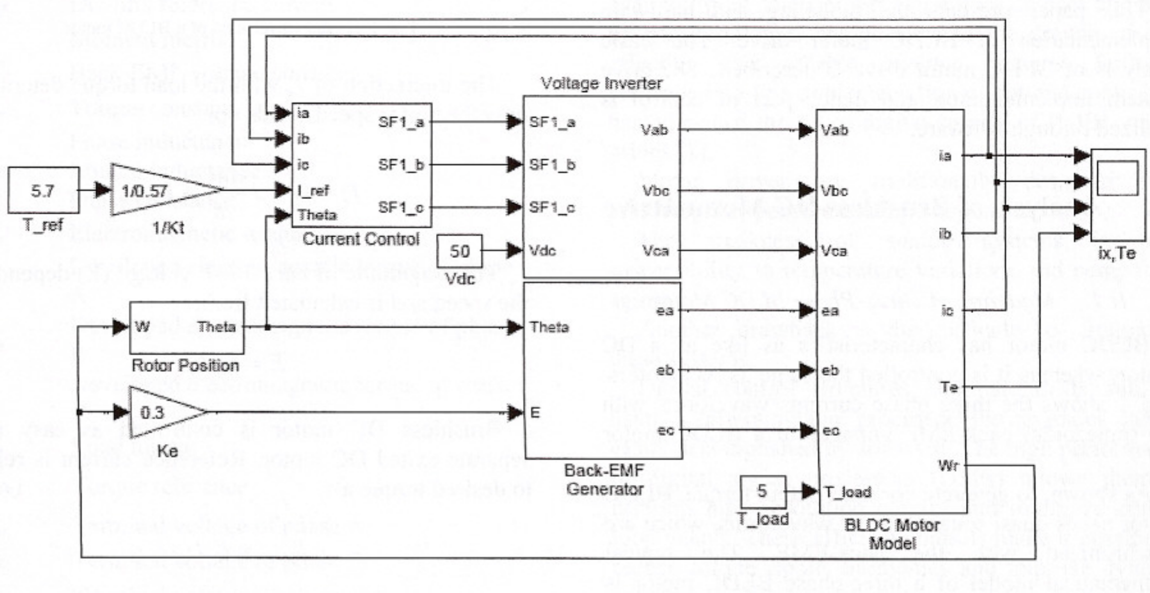
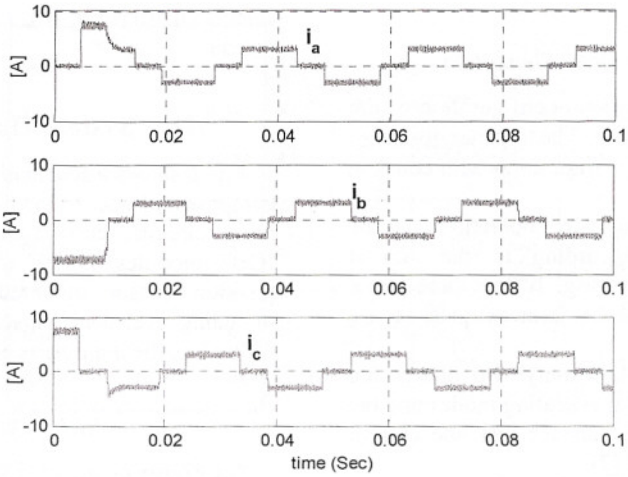
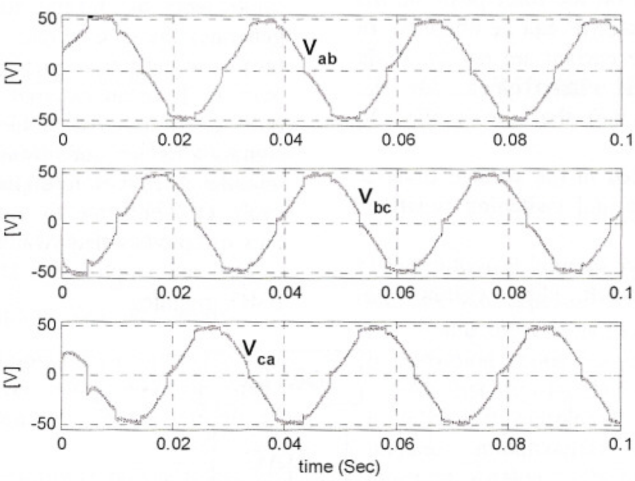


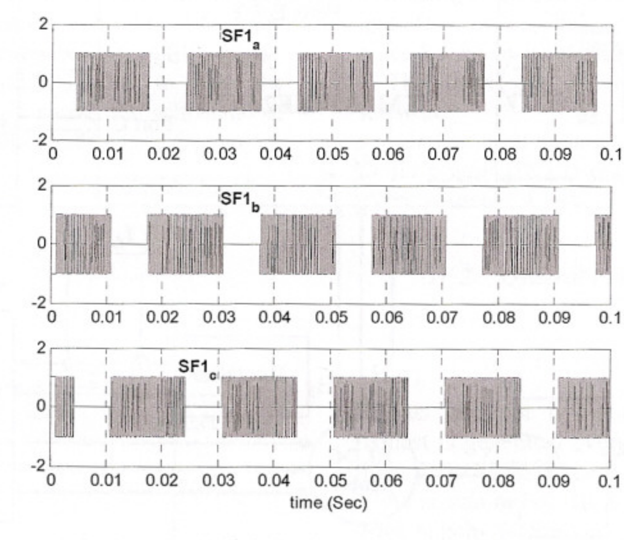
Fig. 4. Implementation of the Brushless DC motor drive in Matlab/Simulink



(a) Phase Currents



(b) Filtered stator line voltages



(c) Switching function signals

Fig. 5. Simulation results of brushless DC motor drive

II.2. BLDC Motor Drive Simulation

Fig. 3 shows the overall system configuration of the three-phase BLDC motor drive. The inverter topology is six-switch voltage-source configuration with constant DC-link voltage (V_{dc}).

The PWM three-phase inverter operation can be divided into six modes according to the current conduction states as shown in Fig. 1. The three phase currents are controlled to take a form of quasi-square waveform.

For this motor, in each time only two phases are excited through the conduction operating modes and the third phase is silent. So, we can use just one current sensor located in the DC-link [7].

Fig. 4 shows the implementation of the BLDC motor drive in Matlab/Simulink software. As shown, in Back-EMF generator block, based on the rotor position, the numerical expression of back-EMF can be obtained. In Current Control block, phase current are regulated via hysteresis current controller. This block out the switching functions (SF1_a,b,c) that are applied to power switches.

Line voltages are calculated in the voltage Inverter block using DC-link voltage and switching functions signals.

Developed line voltages are applied to motor and in the BLDC Motor Model block, phase currents are calculated from Eq. (1). Fig. 5 shows some simulation results.

III. System Hardware Structure

Fig. 6 shows a schematic of the hardware system that composes of the following parts: DSP board, switch drive circuits, current and voltage sensing circuits, IGBT modules, BLDC motor with three Hall Effect position sensor mounted on it and DC-link part including rectifier, capacitor and brake resistor. As following, the main parts are described briefly.

III.1. DSP Controller

An eZdsp board of TMS320LF2407A DSP acts as controller to control the whole of the system [8]-[9].

It reads the current and position feedback, implements the torque control algorithm and finally generates the gate signals. DSP can take the command torque or current from remote via its CAN, SPI, SCI ports or from an external potentiometer into its ADC units or from its data memory. Voltage and current signals after pre-conditioning circuits come into ADC modules to convert to digital signals. At the end of each cycle, DSP generate six independent PWM signals, and outs to opto-isolated switch drivers. The switch drivers isolate and amplify the DSP commands and send to IGBT modules.

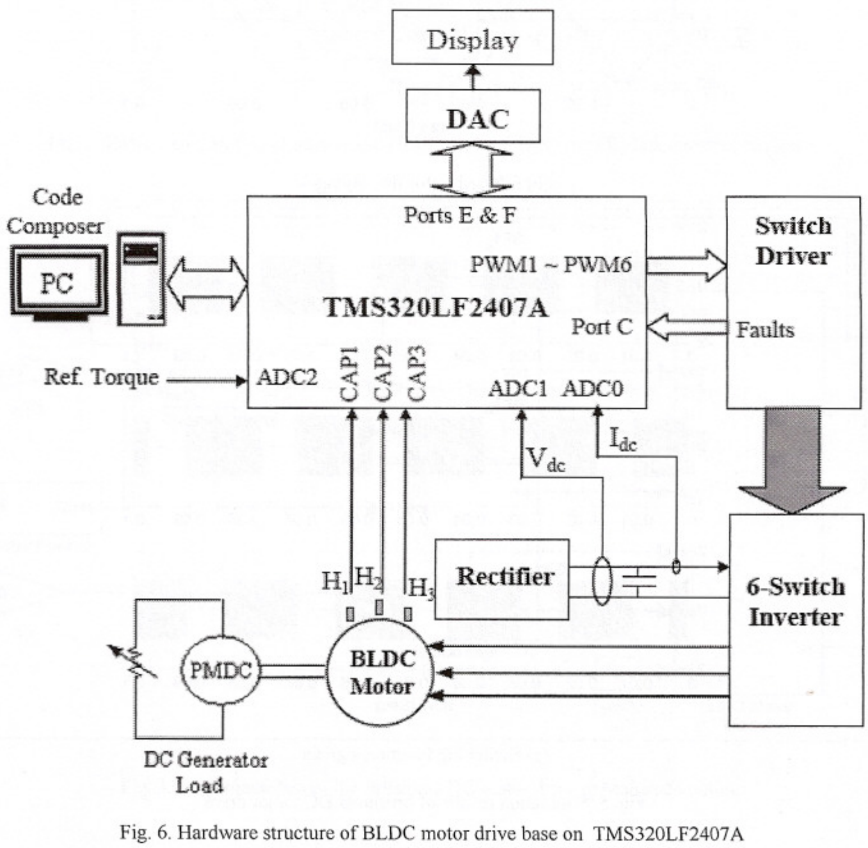


Fig. 6. Hardware structure of BLDC motor drive base on TMS320LF2407A

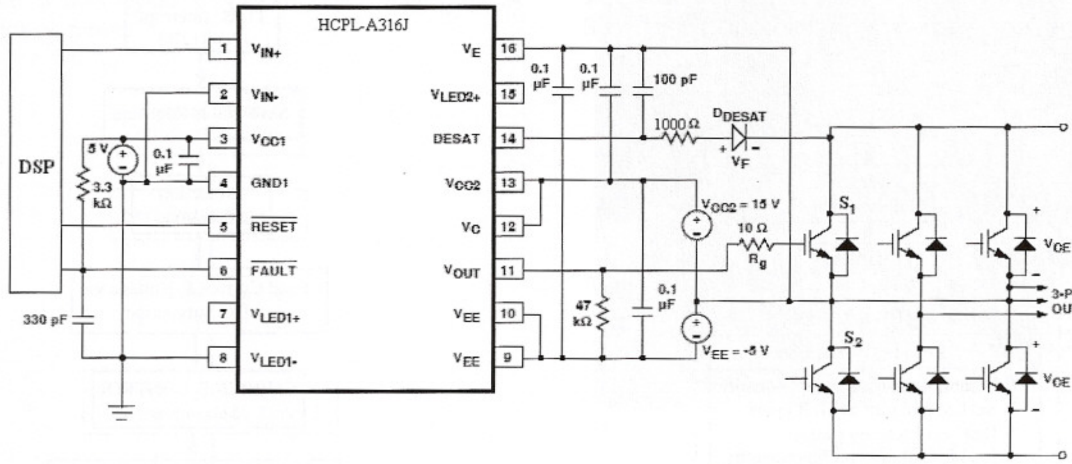


Fig. 7. Circuit schematic of each switch driver board

III.2. Switch Driver Circuit

The output pulses from TMS320LF2407A DSP are not capable of directly driving the IGBTs of higher ratings. Hence device drivers HCPL A316J are used. Six driver circuits are used to drive the IGBTs. Fig. 7 shows the schematic of each A316J drive board.

III.3. Current and Voltage Sensing Circuits

Torque control needs to know the current value. Also o protect the circuit from over voltage and over current conditions or rotor stall condition, some current and voltage sensing is required.

Using resistors causes additional power losses and also has low accuracy. So, we have used isolated current and voltage transducers LA-55P and LV-25P made by LEM, and design conditioning board to apply their output to ADC channel of DSP board. Conditioner, amplify and add DC offset to make the signal between 0~3.3V. Fig. 8 shows the schematic of the current sensing board. Voltage sensing is the same.

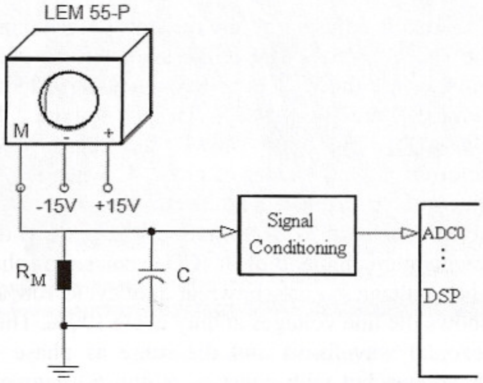


Fig. 8. Circuit schematic of current sensing board

IV. Software Design of the Control System

IV.1. Software Organization

This section presents the overall software structure and the Interrupt subroutine flowcharts. As shown in Fig. 9, the software is based on three modules: System initialization, Protection and the Run module.

The first step for development of the software is to initialize all peripherals on the DSP board, which includes initialization of the PWM ports, timer interrupt, Analog-to-Digital (A/D) converters. Also, the needed variables must be defined in the initialization. The second module checks the healthy of the drive includes power module, DC-link over current/voltage or other favorite conditions.

The third one is the BLDC control dedicated software.

It is based on a waiting loop interrupted by both the Timer 2 unit (INT2) and the Capture unit (INT4) of Event Manager A (EVA).

IV.2. General Interrupt Service Routines

IV.2.1. GISR2 Service Routine

This interrupt is belonged to INT2 level and its request is generated every current loop period with T1 timer period interrupt.

As shown in Fig. 10, before running the instructions, drive healthy is checked through protection subroutine. Interrupt operations performed inside are: Start of Conversion (measuring the variables that come into ADC unit), current/torque regulation, updating the duty cycle, load the compare registers and finally outing the commands to switch drivers through SEQUENCE subroutine.

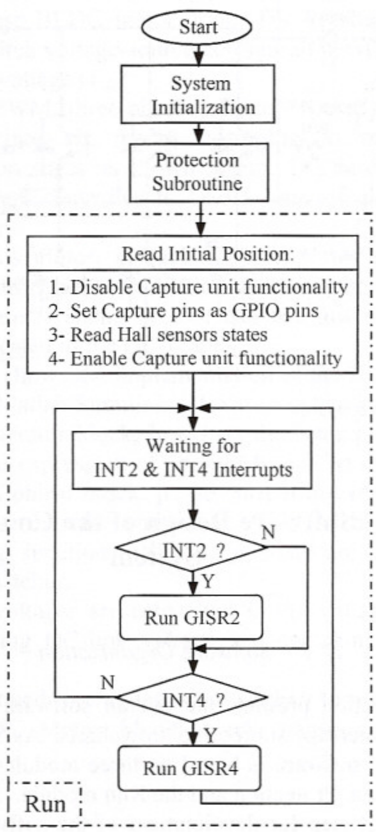


Fig. 9. System software flowchart

T1PR register is set to 500 to have 10 kHz current loop frequency and for current regulation, a PI controller is used.

At the end of GISR2, program jumps to infinite loop and waits for next interrupts.

IV.2.2. GISR4 Service Routine

This interrupt is belonged to INT4 level and its request is generated whenever a pulse level change occurs on the each input pins of Capture unit 1 (CAP1, CAP2, CAP3).

As shown in Fig. 11, firstly the drive healthy is checked. GP Timer 2 is the time base of Capture unit. The value of the GP timer 2 is counted and stored in the corresponding registers when a specified transition is detected on a capture input pin (CAPx). After transition detection, capture pins are configured as GPIO functionality to read the hall sensors states and the motor position is determined.

GISR2 also may calculate the speed via a fixed point division.

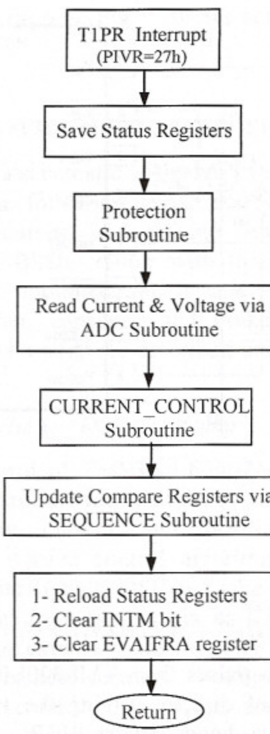


Fig. 10. GISR2 Interrupt service routine flowchart

V. Experimental Results

The experimental test bed as shown in Fig. 12 has been designed and developed in the laboratory. The experimental setup consists of a 300 [W] Brushless DC motor loaded with a Permanent Magnet DC generator. The rated parameters of the BLDC motor are summarized in Table I.

TABLE I
RATED PARAMETERS OF THE BLDC MOTOR

P_{rated}	300 [W]	ω_{rated}	500 [RPM]
T_{rated}	5.7 [N.m]	Z_p	16
I_{rated}	10 [A]	V_{rated}	44 [V]
R_{line} *(2R)*	1.4 [Ω]	K_t	0.57 [N.m/A]
L_{line} *(2*(L-M))*	1 [mH]	K_e	0.3 [V/rpm]

The load is adjusted by the resistor that is connected to the DC generator. The IGBT switches are used for inverter where the switching frequency is 10 kHz. All waveforms are captured via a storage digital oscilloscope. Fig. 13 shows the phase current waveforms and hall sensor of phase A, when the motor operates at stable state and maximum duty cycle. It coincide theoretical waveforms shown in Fig. 4. In Fig. 14, switching command of S_1 IGBT, current of phase A and line voltage V_{ab} are shown at duty cycle 100%. Fig. 15 shows the line voltages at duty cycle 100%. They are trapezoidal waveforms and the same as phase back-EMF voltage but with constant region 60 degree. Fig. 16 shows the switch command of S_1 and S_2 IGBTs line voltage at duty cycle 50%. The line voltages are as PWM waveforms.

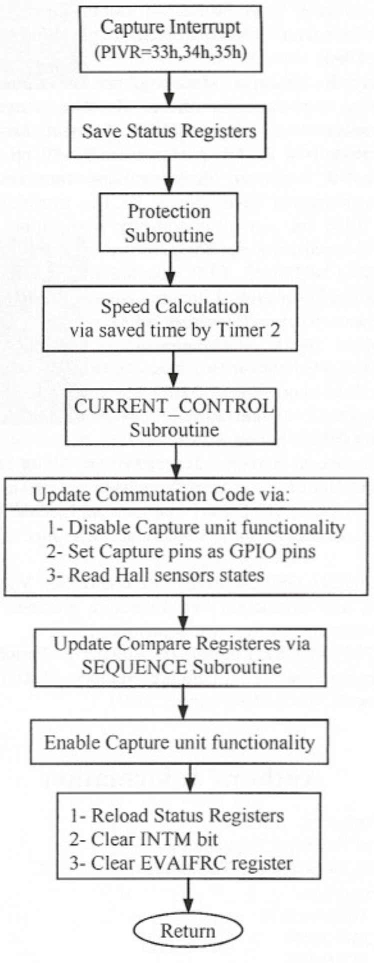
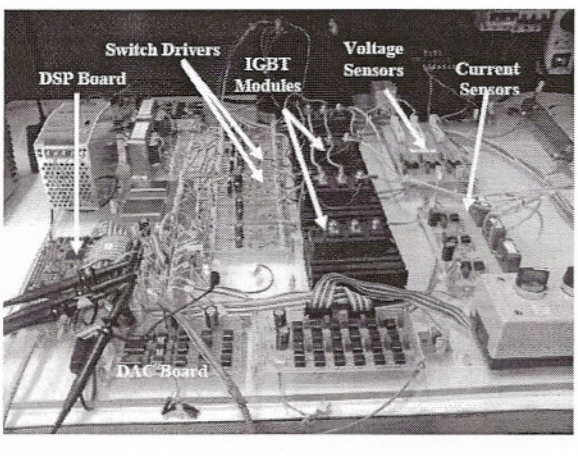
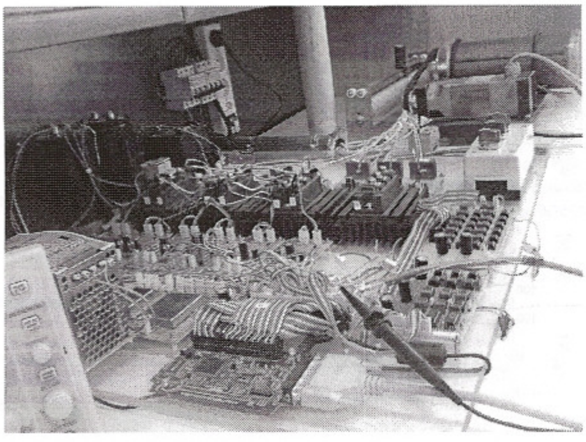


Fig. 11. GISR4 Interrupt service routine flowchart



(a) Main board of the drive



(b) Entire of the drive

Fig. 12. BLDC motor drive system

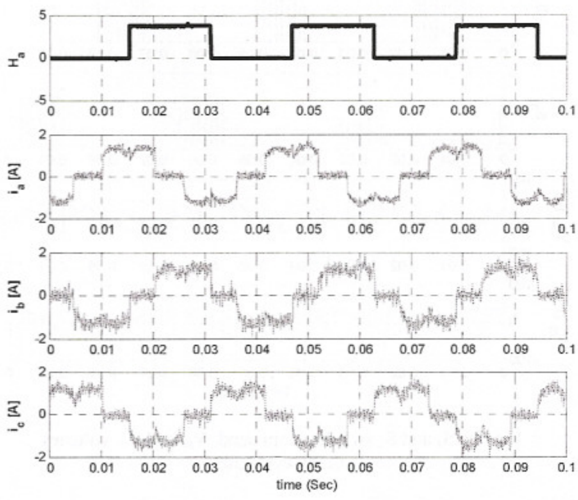


Fig. 13. Phase current waveforms and H_1 signal at duty cycle 100%

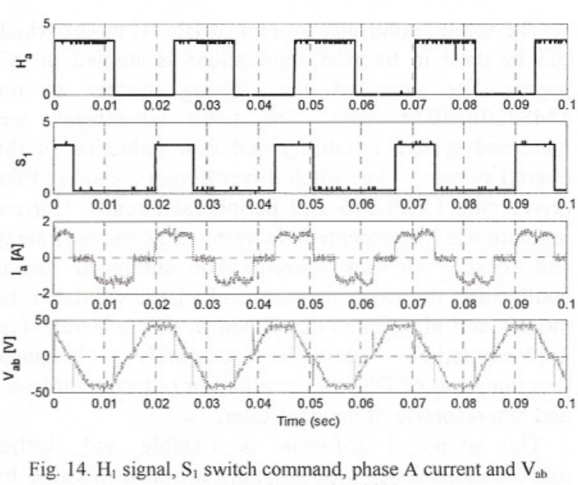


Fig. 14. H_1 signal, S_1 switch command, phase A current and V_{ab} voltage at duty cycle 100%

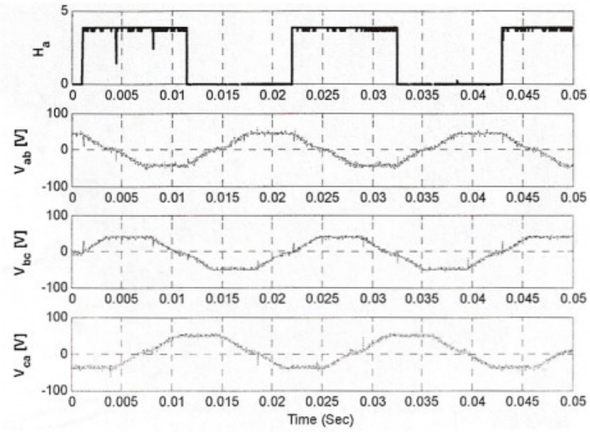


Fig. 15. H_1 signal, line voltages at duty cycle 100%

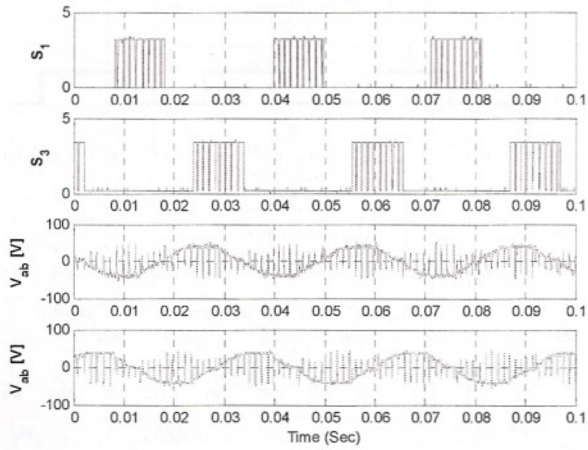


Fig. 16. S_1 and S_3 switches command, V_{ab} and V_{bc} voltages at duty cycle 50%

VI. Conclusion

The torque controller system of BLDC motor which can be used in traction applications is studied in this paper. The core of the driving system is the TMS320F2407A chip. The main advantages are: increased system reliability and cost reduction of the overall system. The switch driver circuit consists of the driver chip HCPL316 and peripheral circuits. Current regulation is implemented via hysteresis control strategy and sensing DC-link current. The simulated results conforming the experimental results have validated the models and algorithms developed in this research. The implementation through assembly language programming of DSP has resulted in reduced hardware and fast response of the controller.

The proposed software is flexible and further modifications in control structure are also possible by changing the software. For example, implementing the sensorless control of brushless DC motor drive can be accomplished by capturing the zero crossing points of line voltages instead of capturing the Hall Effect sensors signals.

References

[1] T J E Miller, Brushless Permanent Magnet and Reluctance Motor Drives (Oxford Science Publication, UK, 1999)

[2] Yasuhiko Dote, Servo Motor and Motion Control using Digital Signal Processors (Prentice Hall, Eagle Wood, cliffs, New Jersey, 1990)

[3] P. Pillay, R. Krishnan, Modeling, simulation, and analysis of permanent-magnet motor drives. I: The permanent-magnet synchronous Motor Drive, IEEE Transactions on Industry Applications, vol. 25, No. 2, March/April 1989, pp. 265-273.

[4] P. Pillay, R. Krishnan, Modeling, simulation, and analysis of permanent-magnet motor drives. II: The Brushless DC Motor Drive, IEEE Transactions on Industry. Applications, vol. 25, No. 2, March/April 1989, pp. 274-279.

[5] TMS320LFLC240xA DSP Controllers Reference Guide-- System and Peripherals, Literature Number: SPRU357B, (Texas Instruments, Revised December 2001).

[6] A. Halvaei Niasar, H. Moghbelli, A. Vahedi, Modeling and Simulation Methods for Brushless DC Motor Drives, Proceeding of the First International Conference on Modeling, Simulation and Applied Optimization (ICMSAO'05), pp.05-446/05-6, February 2005, Sharjah, U.A.E.

[7] B.K. Lee and M. Ehsani Advanced BLDC Motor Drive for Low Cost and High Performance Propulsion System in Electric and Hybrid Vehicles, IEEE 2001 International Electric Machines and Drives Conference, 2001, Cambridge, MA, June 2001, pp. 246-251.

[8] TMS320C24x DSP Controllers Reference Set, Volume 1: CPU, System, and Instruction Set, Literature Number: SPRU160B, (Texas Instruments, Revised September 1997).

[9] TMS320C24x DSP Controllers, Volume 2: Peripheral Library and Specific Devices, Literature Number: SPRU161B, (Texas Instruments, Revised September 1997).

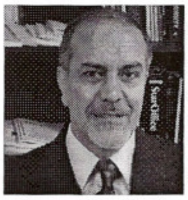
Authors' information

[1]Associate Professor,
Department of Electrical Engineering,
Iran University of Science & Technology,
Narmak, Tehran, Iran
Postal code: 16846-13114
Tel: +98 21 73912619
Fax: +98 21 77240490
E-mail: avahedi@iust.ac.ir

[2]Associate Professor,
Qatar Department of Mathematics,
Texas A&M University,
Po. Box 23874, Doha, Qatar
Department of Electrical & Computer Engineering,
Isfahan University of Technology,
Isfahan, Iran
Tel: +98 218054034
E-mail: moghbeli@math.tamu.edu

[3]Ph.D. Student,
Department of Electrical Engineering,
Iran University of Science & Technology,
Narmak, Tehran, Iran
Tel: +98 913 1635923
Fax: +98 21 77240490
E-mail: ahalvai@yahoo.com

Abolfazl Vahedi received his B.S., M.S. and Ph.D. in 1989, 1992 and 1996 from Ferdowsi Mashhad University, Institut nationale polytechnique de Lorraine (INPL-FRANCE) and INPL all in electrical engineering respectively. He has directed several projects in the area of conventional and special electric machines and drives. His research interests are mainly design, implementation and optimization of electric machines including traction motors and drives. He is a member of Center of excellence for power system automation and operation at Iran university of Science and technology. He is also member of IEE and SEE.



Hassan Moghbeli received his B.S., M.S. and Ph.D. in 1973, 1978 and 1989 from Iran University of Science and Technology (IUST), Oklahoma State University and University of Missouri-Columbia (UMC) all in electrical engineering respectively. He has directed several projects in the area of electric vehicles, hybrid electric and fuel cell vehicles and railway electrification. His research interests are mainly the control, electric drive train, power electronic design of electric vehicles, hybrid electric vehicles, and electric railroads. He is a member of IEEE, ASME, and SAE.

Abolfazl Halvaei Niasar received his B.S. and M.S. in 1998 and 2000 from Isfahan University of technology (IUT) and university of Tehran (UT) both in electrical engineering respectively. He is now studying in Iran University of science & technology (IUST) for Ph.D. His research interests are mainly the control systems & instrumentation, DSP based control, electric drives, PM Brushless DC motor drives, sensorless drives. He is a student member of IEEE.