ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 2, Issue 8, August 2014

Implementation of Predictive Current Controller Using TMS320LF2407A DSP for Closed Loop Control of PMBLDC Motor

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Abstract - Closed loop variable speed operation of a Permanent Magnet Brushless DC(PMBLDC) motor drive covering transient and steady state running conditions has been investigated by experimental work. The motor operates as a prime mover coupled to a dc generator and the entire drive is modeled using a set of electromechanical equations. Hardware implementation of the closed loop system is done using TMS320LF2407A based DSP controller and an intelligent power module covering speed and current feedback and the drive performance results are presented. The control algorithm combines the Space Vector PWM switching requirements and Predictive Current principle. The results confirm the real-time capability of the controller and associated DSP program in a practical operational environment.

Keywords: Closed loop operation, PMBLDC Motor, Predictive current control, Real time DSP Controller, Space vector PWM.

1. INTRODUCTION

Motors using permanent magnets are being used increasingly in modern speed and position control applications [1]. The main advantages of these motors include high power to weight ratio, high torque to current ratio, fast dynamic response, high power factor and minimal maintenance compared with conventional motors [2],[3]. In variable speed control applications, PWM inverters are employed to provide effective control of output torque over a wide range of speed [4]. A PMBLDC motor drive system consists of a variable frequency 3-phase voltage source PWM inverter along with sensing and control circuits. Here, one important requirement is the sensing of rotor position by Hall effect sensors and slaving of the stator frequency and phase to the instantaneous rotor angular position so as to maintain unidirectional torque [2], [5]. Several current control schemes for PWM inverters have been reported in literature, viz., linear controller, hysteresis controller and predictive current controller [6]. Digital controllers allow the drive system to perform with high resolution, minimizes control loop delays and easy up gradation [7] Several publications are available in the area of controllers which provide an improved torque and speed control along with minimization of torque ripples [8-10]. SVPWM of the inverter through a high performance DSP based controller leads to precise control of stator current and reduction of harmonics and torque ripple so as to improve the overall dynamic performance [11].

This paper presents a full experimental set up consisting of a 1.2HP PMBLDC motor coupled to a separately excited DC generator for loading. It is a continuation of the earlier simulation results reported by the authors [12], and focuses on the DSP hardware and programming details. Accordingly, the presentation covers the BLDC motor drive system fed from a 3-phase IGBT PWM inverter and controlled by programming a TMS320LF2407A based DSP controller. A PC system interfaced with the DSP board provides on-line

GUI for user interaction and facilitates DSP program development, instrumentation, monitoring and display. The results cover both transient and steady state aspects of operation of the drive system covering start up transients, speed response to step changes in reference speed setting, fluctuation on the dc link voltage and load torque disturbances. The variation of steady state stator current for corresponding to different reference speed settings has also been determined.

2. PMBLDC DRIVE SYSTEM

Fig. 1 shows the overall block diagram of the PMBLDC drive system. The three phase inverter comprises six numbers of IGBT's in bridge configuration and is fed from a fixed supply. The stator windings of the PMBLDC motor are energized from the variable frequency variable voltage inverter.

The closed loop control scheme consists of acquiring the electrical and mechanical variables of the BLDC motor drive, processing these signals for current, torque and speed control and for generating the IGBT gate trigger

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Vol. 2, Issue 8, August 2014

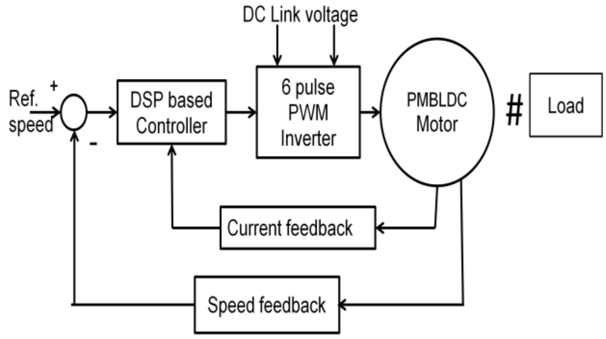

Fig. 1 Overall block diagram

signals to satisfy logic, sequence and timing requirements. The actual shaft speed is compared with the reference value to get the speed error dω which is fed to a PI controller to obtain an actuating signal dT_L. Now the new torque reference equals $T_e^* = T_e + dT_L$ and the reference current i* is computed as $i^* = T_e^*/K_t$ where K_t is the torque constant of the motor.

The PMBLDC motor is coupled to a separately excited dc generator whose excitation and load can be adjusted to set the mechanical characteristic at the BLDC motor shaft. The rotational phenomena associated with the BLDC motor-dc generator set is characterized by friction (belt friction and bearing friction), windage (at both machines), iron and copper losses in the dc generator and torque absorbed by the dc generator for meeting the electrical power output. Of these, the frictional force and therefore the torque remain constant over the running range.

The other torque components corresponding to windage and eddy current loss vary linearly with ω, whereas the torque loss due to hysteresis of the magnetic circuit of armature is nearly constant at the operating range. As far as energy conversion taking place in the dc generator is concerned, both the induced emf and load current at a given resistive load vary in a proportional manner, i.e. E is proportional to ω and I_L is proportional to E. Accordingly the reflected torque T_{Lm} at the BLDC motor shaft at a fixed generator field current is of the form

$$T_{Lm} = K_0 + K_1\omega_r + T_L \quad (1)$$

The dc generator torque T_{Lg} is given by

$$T_{Lg} = K_b \left[\frac{K_b\omega - E_d}{R_a + R_L} \right] \quad (2)$$

where K_b is the back emf constant, ω is the speed of the generator in rad/sec and E_d is the brush drop. The mechanical coupling between the two machines is done using belt drive with a speed reduction of 3:1. The reflected torque on the motor shaft is obtained by dividing the torque obtained from eqn. (2) by 3 and substituting in eqn. (1) for T_L.

3. IMPLEMENTATION OF SVPWM BASED PREDICTIVE CURRENT CONTROLLER

Space vector theory is closely related to the generalized two-axis theory of electrical machines [13]. It is valid for arbitrary variation of instantaneous voltages and currents present in an inverter-fed system. Space Vector PWM [SVPWM] refers to a special technique of determining the switching sequence and timing of the inverter power switches so as to obtain variable output voltages defined spatially [13].

The per phase stator equation are written in terms of the space vector variables as: [12], [14-16]

$$\overline{v_s}(t) = \overline{i_s}R_s + \frac{d\overline{\psi_s}}{dt} + j\omega_r\overline{\psi_s} \quad (3)$$

where $\overline{v_s}(t)$ is the stator voltage space vector, $\overline{i_s}$ is the stator current space vector and $\overline{\psi_s}$ is the stator flux linkage space vector and enables the control of stator phase currents through control of the applied stator voltage space vector, $\overline{v_s}(t)$.

Considering 120^0 conduction mode of operation of the inverter switches, there are 15 possible combinations of ON and OFF states. Among this, only 6 combinations are active for power transfer, which are shown in Table 1. The sector-wise voltage space vectors $\overline{V_1}$ to $\overline{V_6}$, each one having a length of $(1/\sqrt{3})V_{dc}$ form a hexagon.

In predictive current control method [6], the current reference as a sequence of discrete samples is calculated from speed error and dynamic torque-speed characteristic of the drive system as described in Section 2 above. By comparing it with the measured stator current, the error in current space vector is computed. Now, by using the principle of predictive current control, the required value of the voltage space vector is computed so as to minimize this current error as given below.

The voltage space vector at the k^{th} sampling instant is given by [4]

$$v(k) = e(k) + L_{eq}\frac{di(k)}{dt} + Ri(k) \quad (4)$$

where e(k) is the sampled emf space vector, i(k) is the sampled current space vector and L_{eq} is the equivalent stator inductance. R is the resistance of the stator phase winding.

Equation (4) is rewritten using finite differences for calculating v(k) as

$$v(k) = e(k) + \frac{L_{eq}}{T}[i^*(k+1) - i(k)] + Ri(k) \quad (5)$$

where $i^*(k+1)$ is the desired value of the space current vector at the next sampling instant and the controller minimizes the dynamic value of current error $(i^*(k+1)$ -

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ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
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TABLE 1
SPACE VECTOR SWITCHING TABLE

State	v_a	v_b	v_c	v_s	Voltage Vector
1.	$\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$	0	$\frac{V_{dc}}{\sqrt{3}}\angle 330^o$	$\overline{V_1}$
2.	$\frac{V_{dc}}{2}$	0	$-\frac{V_{dc}}{2}$	$\frac{V_{dc}}{\sqrt{3}}\angle 30^o$	$\overline{V_2}$
3.	0	$\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$	$\frac{V_{dc}}{\sqrt{3}}\angle 90^o$	$\overline{V_3}$
4.	$-\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$	0	$\frac{V_{dc}}{\sqrt{3}}\angle 150^o$	$\overline{V_4}$
5.	$-\frac{V_{dc}}{2}$	0	$\frac{V_{dc}}{2}$	$\frac{V_{dc}}{\sqrt{3}}\angle 210^o$	$\overline{V_5}$
6.	0	$-\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$	$\frac{V_{dc}}{\sqrt{3}}\angle 270^o$	$\overline{V_6}$

i(k)) [14-16]. Space vector modulation is used to generate the vector v(k) as shown in Fig. 2. Here v(k) is synthesized in sector1 from the adjacent vectors $\overline{V_1}$ and $\overline{V_2}$ with appropriate duty ratios t_1/T and t_2/T where T is the period of the high frequency modulating signal and t_1, t_2 are subintervals of T, during which the space vector is aligned with $\overline{V_1}$ and $\overline{V_2}$

Resolving the vector v(k) along $\overline{V_2}$ and $\overline{V_1}$,

$$v_2(k) = \frac{2}{\sqrt{3}} v(k) \sin \alpha \quad (6)$$

$$v_1(k) = v(k) \cos \alpha - 0.5 v_2(k) \quad (7)$$

where α is the modulation angle. The duration t_1 and t_2 of the states 1 and 2 in Sector 1 are given by [12], [14-16]

$$t_1 = \frac{v_1(k)}{V_{dc}/\sqrt{3}} T \quad (8)$$

$$t_2 = \frac{v_2(k)}{V_{dc}/\sqrt{3}} T \quad (9)$$

and $$T = t_1 + t_2 + t_0 \quad (10)$$

where t_0 is the zero state duration or inactive state. These values are also sector-specific and used for the generation of symmetrical space vector PWM which leads to a reduction in Total Harmonic Content [THC] in the stator current [6].

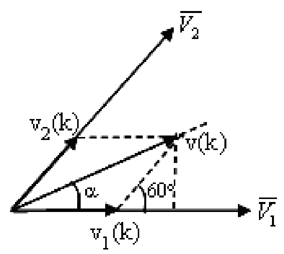

Fig. 2 Synthesis of v(k) in sector 1

4. EXPERIMENTAL WORK

4.1 Experimental Setup

Fig. 3 shows the experimental setup of the entire drive system. The power electronic converter in the drive system consists of two parts: a front end uncontrolled bridge rectifier and a three phase six-switch inverter. The motor windings are star connected and since only two phases will be ON at a time, the magnitude of the dc link current is equal to the phase currents. Thus the dc link current is measured instead of the phase current using a current sensor. The controller was developed based upon TMS320LF2407A DSP chip which is a 16 bit fixed point processor [11], [17]. Use of floating point DSPs avoids arithmetic overflow, saturation and dynamic range problems. But the draw backs are increased memory requirements and a slower execution speed. By using fixed point processors, scaling of input signals and shifting of the respective intermediate and final results are critical to the algorithm implementation. For this a prior knowledge of the dynamic range of the data is essential, which is availed in the program.

The BLDC motor is equipped with three Hall-effect sensors. These sensor outputs are wired to the Capture Unit of the controller, utilizing Timer 2 of the DSP as the time base. The Hall-effect sensors give 180 degree overlapping signals. The rising and falling edges of the sensor output are detected, the corresponding interrupt flag is generated and an interrupt service subroutine is programmed to calculate the speed of the motor [11].

4.2 Major Aspects of DSP Programming

PMBLDC drives usually require an efficient processor to create the appropriate drive sequence. They usually use interrupts and timers and consequently many real time issues concerning multi-tasking have to be addressed. An important step in DSP programming is to develop a working algorithm, which includes algorithm design and in-depth study of the numerical properties of different inputs, intermediate variables and parameters.

The controller is internally provided with Event Manager and is the most important peripheral of the DSP for digital motor control. The controller has to implement many functions in real time like key board monitoring, capturing of motor current values through a 10 bit ADC, and sensing of the timing instants of the three numbers of Hall-effect sensors for calculation of speed for implementing the predictive-current algorithm, based on SVPWM scheme. Here the switching states at the IGBT gates are controlled by the action control register (ACTR) of the event manager. The output pins PWM1- PWM6 of the controller IC deliver the PWM signals to the high voltage driver for triggering the IGBT gates. The communication between the DSP kit and PC is through RS232 serial interface, and the PC serves as the user interface, program store and debugging tool. Fig. 3 shows the flow chart which gives the various steps followed in the assembly language program of DSP. The initialization procedures include the initialization of registers, memory allocations and initializing constants and system variables. Timer 1 underflow interrupt is used for the calculation of actual speed, comparison with the reference speed and generation of the PWM signals to drive the inverter. The duty cycle is recalculated for every interrupt as per the calculation block. Equations covering all the aspects of calculation are included in the calculation block. The compare units have been used to generate the PWM signals. Timer 4 period interrupt is used for this purpose. Timer 3 underflow interrupt is used for the display of speed. The switching states are controlled by the ACTR register. The pattern of signal flow covering the various logic blocks of the DSP controller is shown in Fig..3.

The control programs are written in the Assembly language of the DSP, assembled into object code, converted to ASCII-HEX and finally downloaded to the control board memory. The DSP program is essentially multitasking for covering various real-time events as described in Section 4.2. The user interface provided through the keyboard of the PC and VDU enables monitoring the motor operation through GUI. The set up also permits on-line changing of the reference speed setting through the keyboard during running of the motor, without interrupting the real time PWM waveforms. This enables a reliable closed loop operation of the system and monitoring the performance following a change in the reference speed setting.

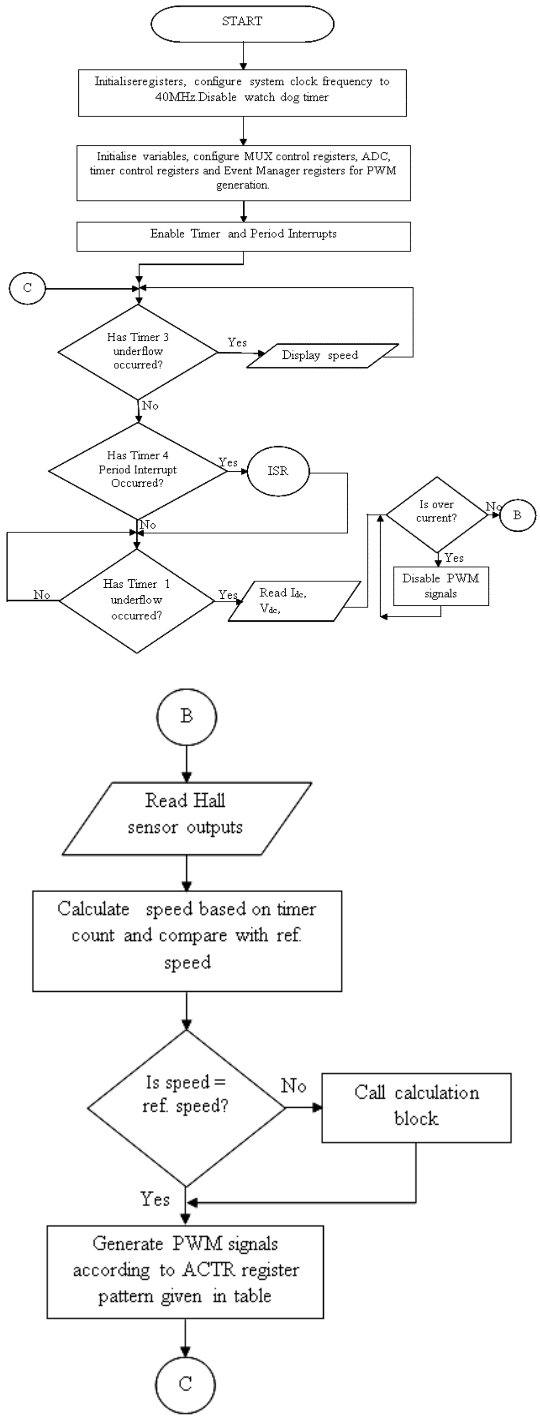

Fig. 3 Flow chart

5. Experimental Results

Experimental work was conducted on a drive system consisting of a 380 V, 2.4 A, 1.2HP BLDC motor coupled to a dc generator. The motor is fed from a 6-pulse voltage source inverter triggered from a DSP controller and the feedback circuits were activated. The different transient problems considered are the start-up behavior under closed loop set up, changes in reference speed, DC link voltage and load torque disturbances as reported by the authors

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Vol. 2, Issue 8, August 2014

[12] where the simulation results and experimental performance are compared. The speed plot of the motor for successive runs was captured on a 2-channel Digital Storage Oscilloscope [DSO]. For good accuracy, the digital train of pulses from the in-built Hall sensors was processed by a circuit incorporating a frequency to voltage converter IC CD4047. The circuit was calibrated over a speed range of 500-1500 rpm for which a linear variation of 3.4 V to 9.4 V was obtained. Fig. 5 and Fig.6 show the startup speed transients for reference speed settings of 500 and 1500 rpm respectively, obtained from experimental work. The dc link voltage was set at 300 V for these runs and the load torque T_L is set at 1.24 Nm.

Fig. 4 Experimental Setup

Fig. 7 shows the speed response for a step increase in reference speed from 500 to 1000 rpm with the motor driving the coupled load. Fig. 8 similarly shows the speed response for a step decrease in reference speed setting from 1500 rpm to 1000 rpm. These indicate the rapid response of the drive and the high performance without any overshoot/undershoot.

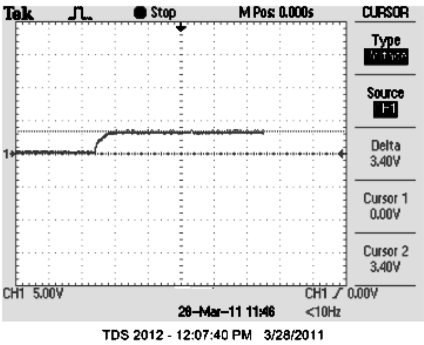

Fig. 5 Startup transients obtained from experiment (Ref. speed = 500 rpm)

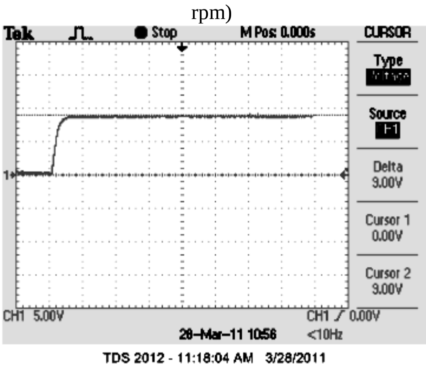

Fig. 6 Startup transients obtained from experiment (Ref. speed = 1500 rpm)

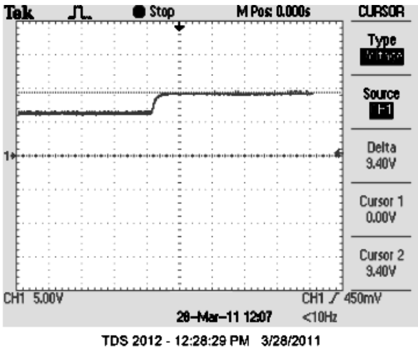

Fig. 7 Speed response for step increase in speed from 1000 rpm to 1500 rpm

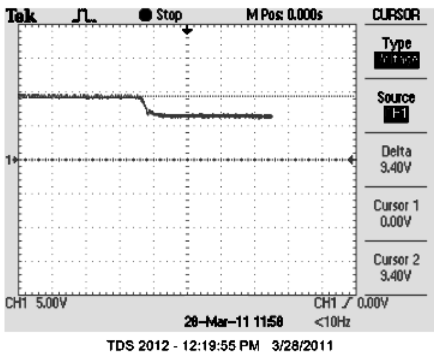

Fig. 8 Speed response for step decrease in speed from 1500 rpm to 1000 rpm

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Fig. 9 shows the variation of the stator current at steady state loaded conditions for a dc link voltage of 300V and T_L of 0.8Nm.

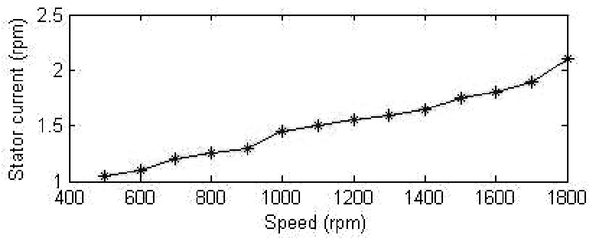

Fig. 9 Variation of stator current with speed

Fig. 10 shows the variation of speed for a decrease in dc link voltage from 300V to 275V for a reference speed setting of 1500 rpm. This was done by quickly decreasing the three phase input using an autotransformer. It is seen that the motor is able to regain the set speed after a momentary drop. Further, two experiments were conducted for testing the drive response for load torque fluctuations, by applying step changes in the coupled generator power output.

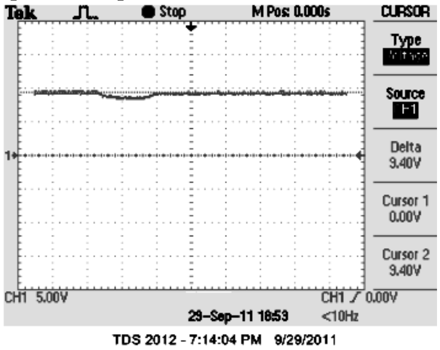

Fig. 10 Speed response for decrease in dc link Voltage from 300 V to 275 V

Fig. 11 shows the variation of speed for an increase in reflected torque on the motor shaft from 0.28Nm to 0.96 Nm and Fig. 12 shows the speed variation for a decrease in reflected torque on the motor shaft from 0.96 Nm to 0.28Nm.

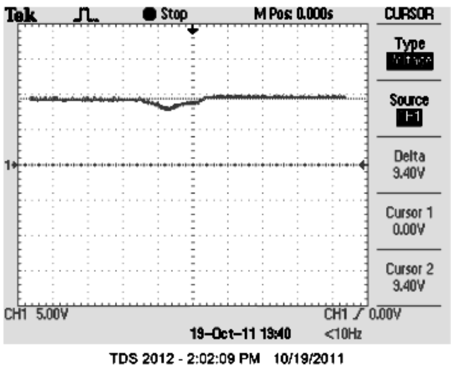

Fig. 11 Speed response for an increase in reflected torque from 0.28 Nm to 0.96 Nm

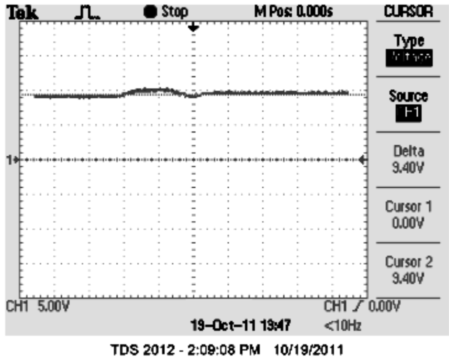

Fig. 12 Speed response for a decrease in reflected torque from 0.96 Nm to 0.28 Nm

4. CONCLUSIONS

The paper deals with the detailed mathematical modeling of a closed loop variable-speed PMBLDC motor drive system under load conditions, operating from 6-pulse voltage fed inverter and provided with speed and current feedback. The control algorithm in terms of a series of equations is presented and is incorporated in the experimental setup. The experimental results bring out the superior transient and steady state performance of the system under different operating conditions. On the experimental side, the physical integration of the PMBLDC drive with an IGBT power module and a TMS320LF2407A based DSP controller along with feedback signals for measurement and control is presented.

The significant features of the DSP processor for data acquisition and control as required in the drive problem along with implementation of the control algorithm in real time by the DSP processor are described. This is followed by the details of the experiments carried out for investigating transient and steady state performance of the drive system. The experimental results reveal the desirable characteristics of system, covering speed control over a wide range, fast dynamic response with negligible steady state error and absence of overshoot/undershoot. This confirms the hardware capability of the DSP chip along with the suitability of the control algorithm for enhancing the performance of a BLDC based drive system.

APPENDIX I

Machine Specifications

BLDC motor

380 V, 3 phase, 2.4 A

R = 6 ohms, L_{eq} = 0.0778H, J = 1.24x10^{-4}kg. m^2

λ = 0.305 Wb, K_t= 0.61 Nm/A

DC generator

0.75kW, 3.4A, 1500 rpm

220V/0.3A Field

ACKNOWLEDGMENT

The authors would like to acknowledge the financial assistance obtained from Centre for Engineering Research and Development (CERD), Govt. of Kerala, for carrying out the experimental work.

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BIOGRAPHY

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He has previously published research papers in Proceedings of IEE (London), International Journal of System Science, International Journal of Power Components & Systems (Taylor & Francis), International Review on Modeling and Simulation and Journal of Institution of Engineers (India). Current interest is in the field of Electric Drives and their Controllers. His major fields of interest are Power Electronics & Drives, Controller development and Microelectronics. He is a Senior Member of the Institution of Engineers (India) and member ISTE.

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She has 9 publications in international journals and 28 national and international conferences at her credit. Area of interest includes robust and adaptive control systems, drives, fuzzy logic, neural network etc. Presently guiding 5 research candidates in the area of control and drives systems. She is a reviewer of Elsevier International journal on Computers and Electrical Engineering, AMSE international journal on modeling and simulation. Presently coordinates 3 research projects and editor of the international journal on electrical sciences being published. She is a life member of ISTE and secretary of ISTE Trivandrum chapter.