DTC CONTROL OF ELECTRICAL DRIVES SYSTEMS WITH BLDC MOTORS

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REZUMAT. Tendințele actuale de limitare a pulsațiilor din cuplul motarelor BLDC au avut în vedere controlul direct al curenților de fază ai acestuia pentru limitarea pulsațiilor ce apar la deconectarea fazelor statorice. În ultima perioadă a crescut interesul pentru controlul direct al cuplului electromagnetic dezvoltat de motoarele BLDC în detrimentul controlului indirect al curentului tocmai în ideea de a obține performanțe dinamice superioare. În acest fel asistăm la o diminuare a riplului datorat comutării fazelor statorice şi a timpului de răspuns în cuplu comparativ cu metodele PWM convenționale.

Cuvinte cheie: Maşină de curent continuu fără perii, Controlul direct al cuplului, procesor numeric de semnal.

ABSTRACT. Current trends to limit the torque pulsation of BLDC motors have considered the direct control of the phase current to limitit the pulsations arising from disconnecting the stator windings. In recent years increased interest in direct control of electromagnetic torque developed by BLDC motors detrimental to indirect current has determined superior dynamic performance. Thus we see a decrease due to switching ripple phase stator and torque response time compared to conventional PWM methods.

Keywords: Brushless machines, Torque control, Digital signal processors, Digital control.

1. INTRODUCTION

Brushless Direct Current (BLDC) motor with trapezoidal shape Back-Electromotive Force (BEMF) drives have been extensively used in many applications. They are used from servo applications to traction drives due to several important advantages such: high efficiency, high power density, large torque to inertia ratio and simplicity of control [1]. They are improving performance and efficiency through more complex control mechanism, so they introduce enough values to justify any added design and component costs. BLDC motor fed by two-phase conduction mode scheme has higher power/height and torque/current ratios. It is less expensive due to the concentrate windings on the stator compared to Permanent Magnet Synchronous Motor (PMSM). The stator flux is controlled by varying current, but constant flux amplitude is determined by feeding with constant current the stator coils and by constant flux permanent magnet interaction. The rotor is spinning at the same frequency as the stator field. The angle between those two fluxes determines the amount of generated torque. The rotor position should be measured or estimated in order to achieve synchronization and high-performance control.

Driving BLDC motor through commutation is fairly simply, resulting in savings in motor design, electronic controls and higher overall weight. Because of permanent magnet presence on the rotor is required less current to drive the motor, leading to improve the efficiency of the drive. Trapezoidal control has traditionally been the more common method due to lower cost and controllers’ simplicity. Trapezoidal control has torque ripple at commutations, is more difficult to control at high speeds and doesn’t work with distributed windings.

Many permanent magnet motors are used in application that requires a rapid and accurate torque response. To simplify torque control, we can assume that output torque is proportional to applied current [2]. Torque pulsation in BLDC drives are generally resulted from the deviation from ideal conditions related to the design factors of the motor (*cogging torque component*) or to the power inverter current excitation resulting in non-ideal current waveforms (*excitation component*) [3]. Many permanent magnet motors use surface mounted magnets with low saliency. If the waveform of phase current and the phase BEMF are perfectly matched, torque ripple is minimized. Cogging torque is created by the stator slots interacting with the rotor magnetic field and is independent of stator current excitation. Excitation torque ripple is caused by the commutation between phases in two-phase control scheme.

Direct Torque Control of BLDC motor has many advantages and it is different from the conventional vector control applied in PMSM, for example: has high dynamic performance concerning BLDC torque, simple control structure, strong robustness to the motor parameters variety, the position sensor can be removed because the torque/flux is estimated from electrical parameters of the motor, so doesn't need accurate position information [4]. DTC has been successfully implemented on induction machines and more recently on permanent magnet synchronous machine.

2. ESTIMATION OF ELECTROMAGNETIC TORQUE

For nonsalient-pole machine with non-sinusoidal shape of BEMF, the electromagnetic generated torque can be expressed by equalization of electrical power absorbed and mechanical power at the output of the BLDC motor such:

$$\begin{aligned}
&\sum_{k=a,b,c} e_{sk}\cdot i_{sk} = m_e\cdot\omega_e \Rightarrow m_e\cdot\omega_e = \\
&= \frac{3}{2}\cdot\left[i_{s\alpha}\cdot\frac{d}{dt}\Psi_{m\alpha} + i_{s\beta}\cdot\frac{d}{dt}\Psi_{m\beta}\right] = \\
&= \frac{3}{2}\cdot\omega_e\cdot\left[i_{s\alpha}\cdot\frac{d}{d\theta_e}\Psi_{m\alpha} + i_{s\beta}\cdot\frac{d}{d\theta_e}\Psi_{m\beta}\right] \Rightarrow \\
&\Rightarrow m_e = \frac{3}{2}\cdot\left[i_{s\alpha}\cdot\frac{d}{d\theta_e}\Psi_{m\alpha} + i_{s\beta}\cdot\frac{d}{d\theta_e}\Psi_{m\beta}\right]
\end{aligned} \tag{1}$$

If *p*, which is the number of poles, is greater than two then in *α-β* reference frame electromagnetic torque can be expressed like in [5] as being:

$$m_e = \frac{3}{2}\cdot\frac{p}{2}\left[i_{s\alpha}\cdot\frac{d}{d\theta_e}\Psi_{m\alpha} + i_{s\beta}\cdot\frac{d}{d\theta_e}\Psi_{m\beta}\right] \tag{2}$$

$$m_e = \frac{3}{2}\cdot\frac{p}{2}\left[i_{s\alpha}\cdot\frac{e_\alpha}{\omega_e} + i_{s\beta}\cdot\frac{e_\beta}{\omega_e}\right], \tag{3}$$

where:

-m_e is electromagnetic torque generated by the BLDC motor;

-p is the number of magnetic poles;

-$i_{s\alpha}$, $i_{s\beta}$ are α-β components of stator winding current;

-$\Psi_{m\alpha}$, $\Psi_{m\beta}$ are α-β components of rotor flux linkage;

This paper considers the application of DTC in two-phase conduction scheme of BLDC drive in order to achieve instantaneous torque control and torque ripple minimization. Experimental results are presented to show the application of DTC in two-phase conduction mode of BLDC drive.

-e_α, e_β are *α-β* components of BEMF;

-θ_e is the electrical rotor position.

3. ESTIMATION OF FLUX LINKAGE

Using transformation, the state space equation of BLDC motor α–β axis stationary reference frame can be written like in [6]:

$$\begin{aligned}
V_{s\alpha} &= R\cdot i_{s\alpha} + L\cdot\frac{di_{s\alpha}}{dt} + e_\alpha \\
V_{s\beta} &= R\cdot i_{s\beta} + L\cdot\frac{di_{s\beta}}{dt} + e_\beta
\end{aligned}, \tag{4}$$

where:

-$V_{s\alpha}$, $V_{s\beta}$ are α-β components of stator windings voltage;

-$i_{s\alpha}$, $i_{s\beta}$ are α-β components of stator windings current;

-e_α, e_β are α-β components of BEMF;

-R and L are the stator resistance and stator inductance.

The flux linkage on each phase has three components:

-one component due to phase current;

-one component due to mutual inductances;

-one component due to magnetic field generated by permanent magnet.

Starting from these considerations, the expressions of stator flux linkage are:

$$\begin{aligned}
\Psi_{sa} &= L\cdot i_{sa} + M\cdot i_{sb} + M\cdot i_{sc} + \Psi_{ma} \\
\Psi_{sb} &= L\cdot i_{sb} + M\cdot i_{sc} + M\cdot i_{sa} + \Psi_{mb}\ , \\
\Psi_{sc} &= L\cdot i_{sc} + M\cdot i_{sa} + M\cdot i_{sb} + \Psi_{mc}
\end{aligned} \tag{5}$$

where:

-Ψ_{sa}, Ψ_{sb}, Ψ_{sc} are a,b,c reference frame components of stator flux-linkage;

-Ψ_{ma}, Ψ_{mb}, Ψ_{mc} are a,b,c reference frame components of stator flux-linkage;

-i_{sa}, i_{sb}, i_{sc} are a,b,c reference frame components of stator windings current;

-L and M are stator inductance and stator mutual inductance.

If the BLDC motor windings are star connected the sum of phase currents is zero. Also, if are neglected the mutual influences of windings, in α-β reference stator frame, the expression of flux-linkage becomes:

$$\begin{aligned}\Psi_{s\alpha} &= L \cdot i_{s\alpha} + \Psi_{m\alpha} \\ \Psi_{s\beta} &= L \cdot i_{s\beta} + \Psi_{m\beta}\end{aligned} . \tag{6}$$

By integration of (4) end equalization with (6) can be obtained the following stator flux-linkage expressions:

$$\begin{aligned}\Psi_{s\alpha} &= \int (V_{s\alpha} - R \cdot i_{s\alpha})dt \\ \Psi_{s\beta} &= \int (V_{s\beta} - R \cdot i_{s\beta})dt\end{aligned} . \tag{7}$$

The magnitude of stator flux vector and the angular position is obtained from relations:

$$\Psi = \sqrt{\Psi^2{}_{s\alpha} + \Psi^2{}_{s\beta}}\ ;\ \theta_e = \mathrm{tg}^{-1}\left(\frac{\Psi_{s\beta}}{\Psi_{s\alpha}}\right). \tag{8}$$

For a surface-mounted permanent magnet rotor, the flux-linkage stationary components are given by:

$$\begin{aligned}\Psi_{m\alpha} &= \Psi_{s\alpha} - L \cdot i_{s\alpha} \\ \Psi_{m\beta} &= \Psi_{s\beta} - L \cdot i_{s\beta}\end{aligned} . \tag{9}$$

Two-phase conduction wave current control causes the locus of the stator flux-linkage to be unintentionally kept in hexagonal shape if the free-wheeling diode effect and BEMF influence to unexcited open-phase are neglected, which can be seen in Fig. 1.

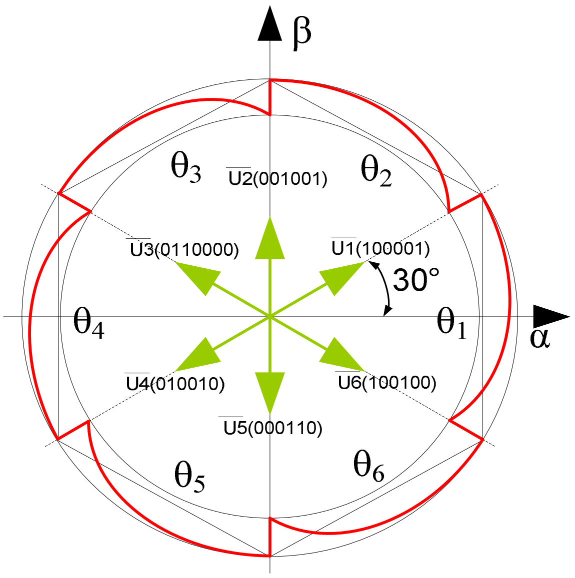

Fig. 1. Locus of the stator flux-linkage vector.

Because of free-wheeling effect caused by the phase's commutation sharp dips occurs at every 60 electrical degrees. That is the reason because the flux-linkage amplitude is hard to be controlled. The basic principle of DTC is to control the stator flux-linkage in such a way that the magnitude is kept constant and its rotational speed must be controlled as fast is possible in order to increase the dynamic torque response.

3. SELECTING OPTIMAL VOLTAGE VECTOR

By assuming that primary windings are star connected and the BLDC motor is fed by an inverter using two-phase conduction mode, the phase voltages are determined by the status of those six inverter switches. Because both phase leg switches can be simultaneously off in two-phase conduction mode, six digits are required for the inverter operation, one digit for each switch. Therefore, are six non-zero voltage vectors for two-phase control scheme. The six voltage vectors are 60 electrical degrees apart from each other, but 30 electrical degrees phase shifted from the corresponding six voltage vectors which are used in three-phase conduction mode of DTC control PMSM's drive, as can be seen in Fig. 1.

To select the voltage vectors for controlling the amplitude of stator flux-linkage the voltage vector plane is divided into six regions [1]. In each region two adjacent voltage vectors can be selected in order to increase or decrease the flux-linkage magnitude. Fig. 2 illustrates how to select voltage vectors for keeping stator flux-linkage within a hysteresis band when stator flux vector is rotating in counter clockwise direction.

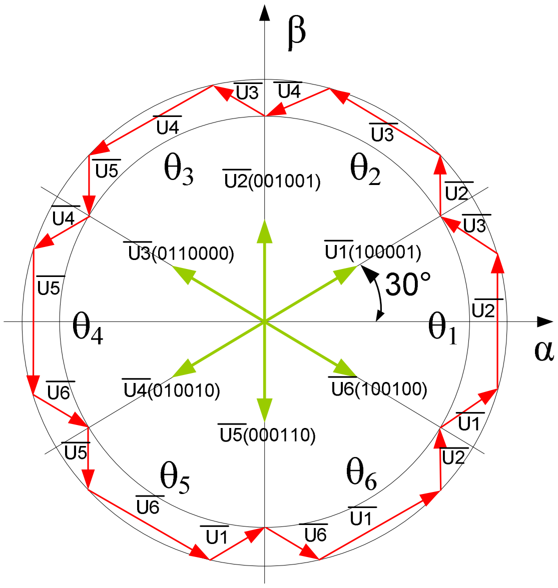

Fig. 2. Optimal stator flux-linkage vector selection.

The torque is controlled by fast controlling the rotational speed of the stator magnetic field and by keeping the angle between stator flux vector and rotor flux vector within admissible range.

4. HARDWARE CONSIDERATIONS

The derivative of rotor synchronous frame components obtained from (2) over electrical position will cause problems mainly due to sharp dips at commutation in two-phase mode control scheme of BLDC drive.

To eliminate this drawback a BEMF in α–β plane vs. electrical position look-up table can be created. This is possible when the drive has un optical encoder mounted at the shaft of the BLDC motor. Usually, a BLDC motor has three Hall-effect position sensors mounted on the stator or at the end of the motor, placed at 120 electrical degrees apart. The resolution of Hall-effect sensors block is enough to control BLDC motor, but in this case a high resolution position signal is needed in order to have a good approximation of the torque using BEMF vs. position look-up table. A good way to increase the six step signal resolution provided by those three Hall-effect sensors is to use an angle observer, which has the scope to eliminate de oscillations from input signal and to provide a continuous high resolution output signal. This kind of observer can be a Phase Locked Loop (PLL) structure observer. In Fig. 3. is illustrated the block diagram of the DTC structure implemented [7].

5. SOFTWARE CONSIDERATIONS

The control algorithm was implemented in C programming language [8] and adapted to DSP using Code Composer 3.5. platform. The algorithm exploits the future of Pulse Width Modulation (PWM) Module to generate interrupt at every new cycle. The PWM signal frequency is 10 kHz, so the interrupt routine is called at every 100 µs. This routine include voltage vector computing, three phase to stationary frame transformation, BEMFs computing from Look Up Table (LUT) with rotor position input information, torque/flux estimation, hysteresis controller implementation and optimal voltage vector selection. Because the inverter switches has riches the maximum operation frequency, in order to eliminate de high frequency ripple from torque I have implemented a LUT technique to modulate the voltage. The modulation index is established by an average voltage corresponding to instantaneous speed of the motor. The flowchart of the main routine is illustrated in Fig. 4.

6. EXPERIMENTAL RESULTS

A drive prototype for home appliance applications, composed of a trapezoidal BEMF machine with stator windings star connected, a full bridge insulated gate bipolar transistor (IGBT) inverter and a 32-bit fixed-point digital signal processor (DSP) in which the aforementioned control algorithm resides, has been built and tested. The DSP can be able to obtain sufficient resolution on the controller gains, an important feature in order to guarantee correct dynamic behavior of the observer. The initial position is represented by a mean value of position corresponding to the initial sector read from Hall sensors. The BLDC machine has the following parameters as can be seen in Table 1.

Table 1

Rated Values of the Motor Prototype.

Rated parameters	Symbol	Value	Unit
Stator resistance	R	0.63	Ω
Stator inductance	L	0.00468	H
Total inertia	J	0.00824	$kg \cdot m^2$
Magnets flux linkage	λ_{pm}	0.262	V·s
Rated speed	n_n	2000	rpm
Rated current	I_n	5	A
Number of poles	p	4	-

The inverter switching frequency is set to 10 kHz and the dead time is 2.5 µs. An incremental encoder with 1000 pulses per rotation has been mounted on the drive's shaft only to allow a comparison between the estimated angle and a high-resolution measurement. The general view of the test bench can be seen in Fig. 5.

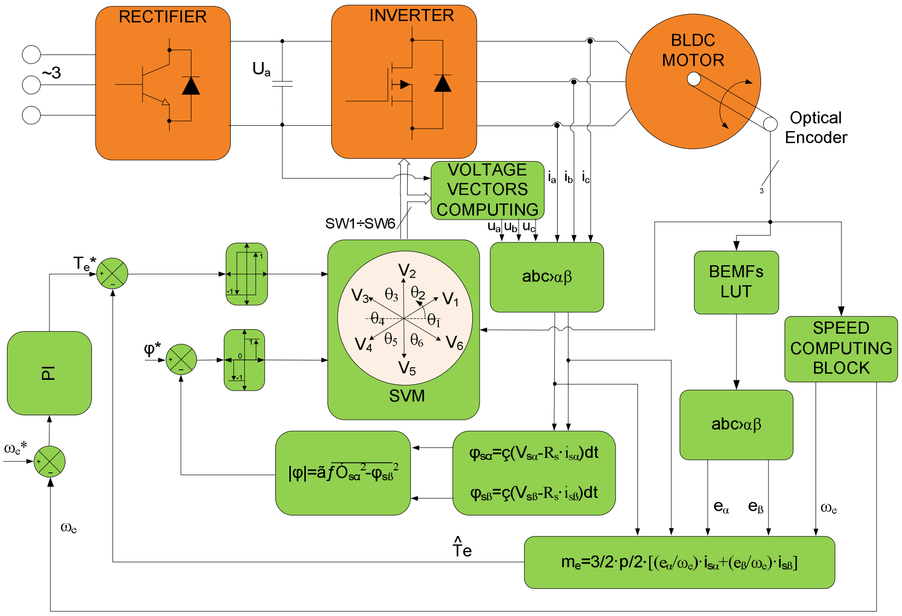

Fig. 3. DTC block diagram.

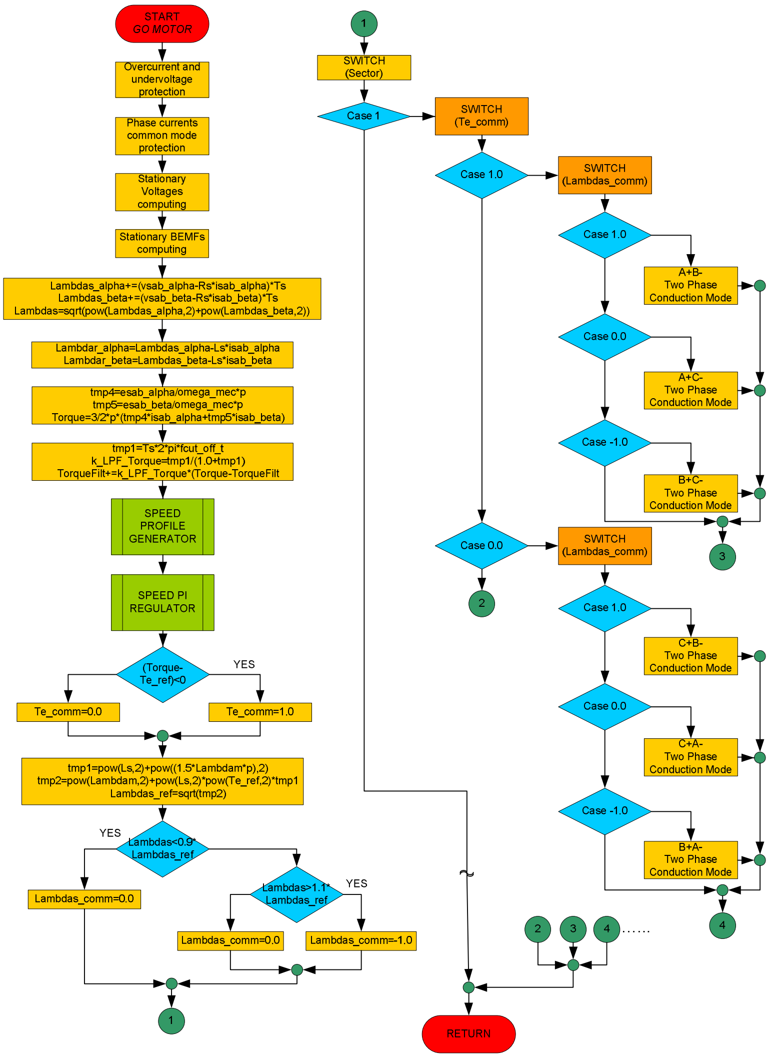

Fig. 4. Flowchart of DTC main routine.

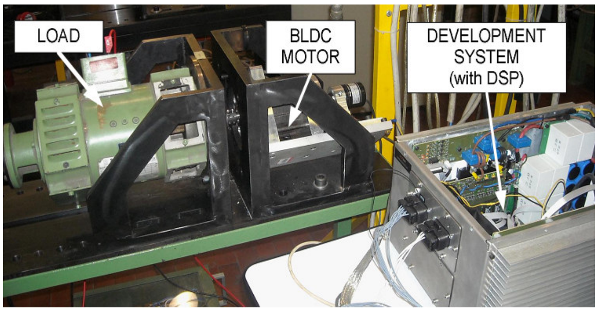

Fig. 5. General view of the test bench.

The optimal voltage vector selection was achieving by following the voltage vectors described in Table 2.

Table 2

Optimal voltage vector selection table.

Torque command	Flux Linkage command	Sector					
		I	II	III	IV	V	VI
1	1	U1	U2	U3	U4	U5	U6
	0	U2	U3	U4	U5	U6	U1
	-1	U3	U4	U5	U6	U1	U2
0	1	U1	U2	U3	U4	U5	U6
	0	U0	U0	U0	U0	U0	U0
	-1	U3	U4	U5	U6	U1	U2

The experimental results were developed in the following conditions:

-steady-state operating mode (Fig. 6);

-step change of reference speed (Fig. 7, Fig. 8);

-step variation of load torque (Fig. 9).

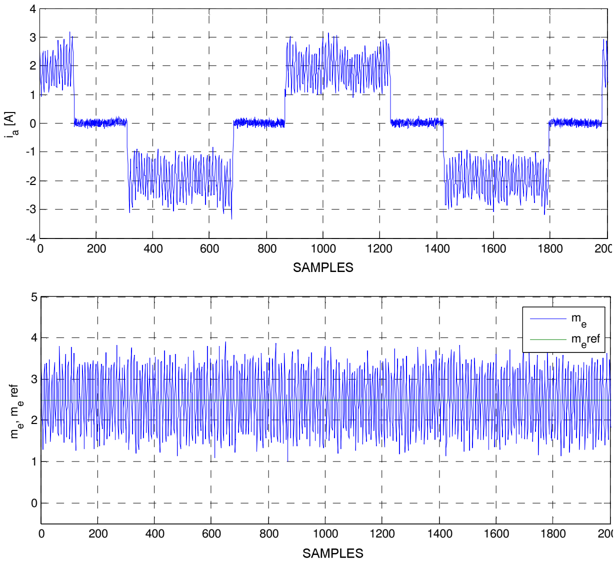

Fig. 6. Steady-state operating mode phase current and torque waveforms.

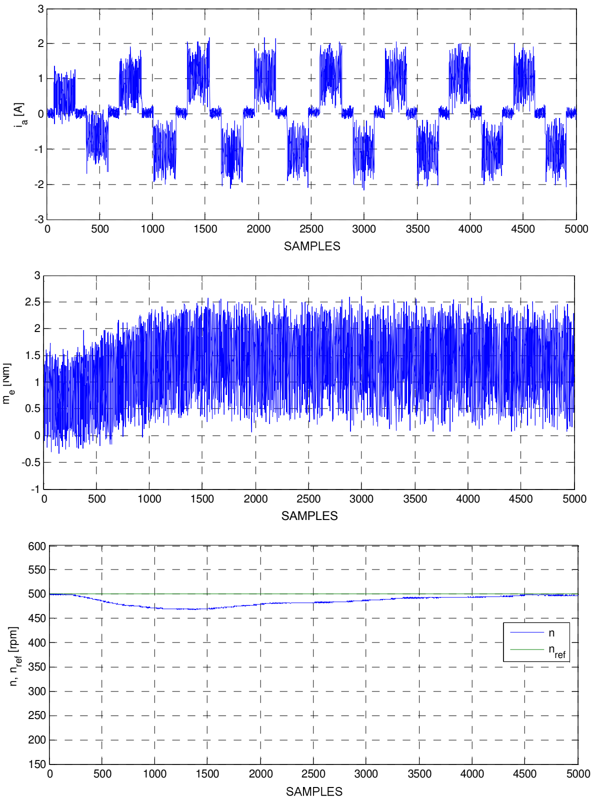

Fig. 7. Load rising condition waveforms (phase current, electromagnetic torque, speed).

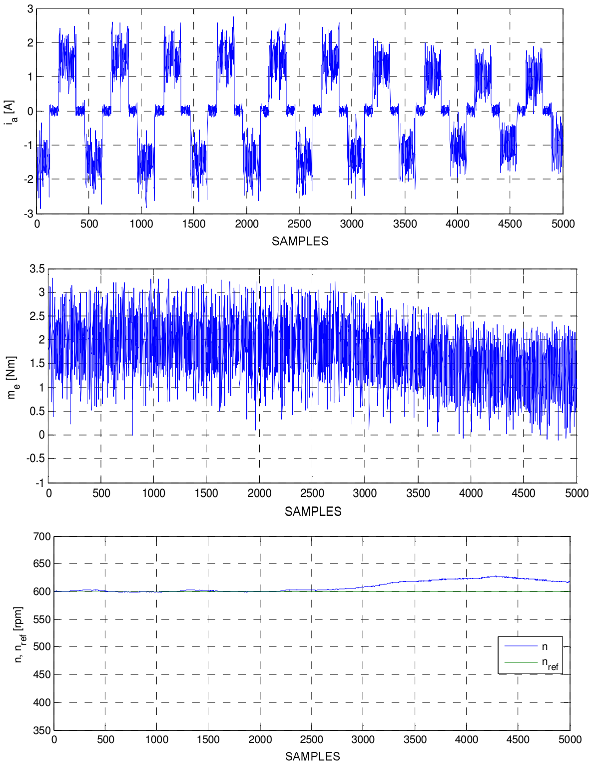

Fig. 8. Load falling condition waveforms.

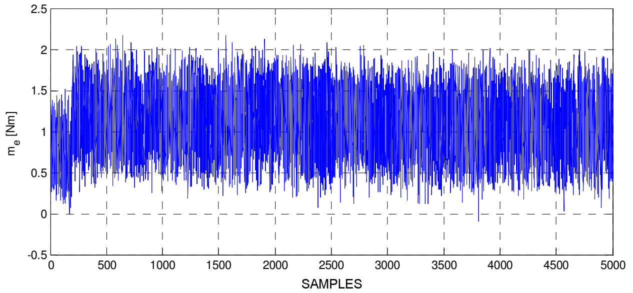

Fig. 9. Load in step modification condition waveform.

7. CONCLUSIONS

DTC has been applied to a BLDC drive, and its utility has been validated by measurements on BLDC motor which have non-sinusoidal BEMF waveforms. It has been shown that DTC is capable of instantaneous torque control and, thereby, of reducing torque pulsations. This study has successfully demonstrated application of the proposed two-phase conduction DTC.

A look-up table for the two-phase voltage selection is designed to provide faster torque response both on rising and falling conditions.

Compared to the three phase DTC technique (used for PMSM), this approach eliminates the flux control and only torque is considered in the overall control system.

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