

Direct Torque Control of Brushless DC Motor with Non-sinusoidal Back-EMF

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Abstract—In this paper, a direct torque control (DTC) technique for brushless dc (BLDC) motors with non-sinusoidal back-EMF operating in the constant torque region is presented. This approach introduces a two-phase conduction mode as opposed to the conventional three-phase DTC drives. In this control scheme, only two phases conduct at any instant of time. Unlike conventional six-step PWM current control, by properly selecting the inverter voltage space vectors of the two-phase conduction mode from a simple look-up table at a predefined sampling time, the desired quasi-square wave current is obtained. Therefore, a much faster torque response is achieved compared to conventional PWM current control. In this paper, it is also shown that in the constant torque region under the two-phase conduction DTC scheme, the amplitude of the stator flux linkage cannot easily be controlled due to the sharp changes and the curved shape of the flux vector between two consecutive commutation points in the stator flux linkage locus. Furthermore, to eliminate the low-frequency torque oscillations caused by the non-ideal trapezoidal shape of the actual back-EMF waveform of the BLDC motor, a pre-stored back-EMF versus position look-up table is designed. As a result, it is possible to achieve DTC of a BLDC motor drive with faster torque response due to the fact that the voltage space vectors are directly controlled while the stator flux linkage amplitude is deliberately kept almost constant by ignoring the flux control in the constant torque region. Since the flux control along with PWM generation is removed, fewer algorithms are required for the proposed control scheme. A theoretical concept is developed and the validity and effectiveness of the proposed DTC scheme are verified through the simulations and experimental results.

Index Terms—Direct torque control, brushless dc motor drives, non-sinusoidal back-EMF, two-phase conduction, fast torque response, low-frequency torque ripples.

I. INTRODUCTION

PERMANENT magnet synchronous motor (PMSM) with sinusoidal shape back-EMF and brushless dc (BLDC) motor with trapezoidal shape back-EMF drives have been extensively used in many applications. They are used in

applications ranging from servo to traction drives due to several distinct advantages such as high power density, high efficiency, large torque to inertia ratio, and better controllability [1]. Brushless dc motor (BLDC) fed by two-phase conduction scheme has higher power/weight, torque/current ratios. It is less expensive due to the concentrated windings which shorten the end windings compared to three-phase feeding permanent magnet synchronous motor (PMSM) [2]. The most popular way to control BLDC motors is by PWM current control in which a two-phase feeding scheme is considered with variety of PWM modes such as soft switching, hard-switching, and etc. Three hall-effect sensors are usually used as position sensors to detect the current commutation points that occur at every 60 electrical degrees. Therefore, a relatively low cost drive is achieved when compared to a PMSM drive with expensive high-resolution position sensor, such as optical encoder.

Direct torque control scheme was first proposed by Takahashi [3] and Depenbrock [4] for induction motor drives in the mid 1980s. More than a decade later, in the late 1990s, DTC techniques for both interior and surface-mounted synchronous motors (PMSM) were analyzed [5]. More recently, application of DTC scheme is extended to BLDC motor drives to minimize the torque ripples and torque response time as compared to conventional PWM current controlled BLDC motor drives [6]. In [6], the voltage space vectors in a two-phase conduction mode are defined and a stationary reference frame electromagnetic torque equation is derived for surface-mounted permanent magnet synchronous machines with non-sinusoidal back-EMF (BLDC, and etc.). It is claimed that the electromagnetic torque and the stator flux linkage amplitude of the DTC of BLDC motor under two-phase conduction mode can be controlled simultaneously.

In this paper, the DTC of a BLDC motor drive operating in two-phase conduction mode, proposed in [6], is further studied and simplified to just a torque controlled drive by intentionally keeping the stator flux linkage amplitude almost constant by

eliminating the flux control in the constant torque region. Since the flux control is removed, fewer algorithms are required for the proposed control scheme. However, it will be shown that the stator flux linkage amplitude and the electromagnetic torque of a BLDC motor cannot be controlled simultaneously in the constant torque region by using the two-phase conduction mode. Moreover, it will be explained in detail that there is no need to control the stator flux linkage amplitude of a BLDC motor in the constant torque region. The stator flux linkage position in the trajectory is helpful to find the right sector for the torque control in sensorless applications of BLDC motor drives. Therefore, the torque is controlled while the stator flux linkage amplitude is kept almost constant on purpose. Furthermore, simulations show that using the zero inverter voltage space vector suggested in [6] only to decrease the electromagnetic torque could have some disadvantages, such as generating more frequent and larger spikes on the phase voltages that deteriorate the trajectory of the stator flux-linkage locus, increase the switching losses, and contributes to the large common-mode voltages that can potentially damage the motor bearings [7]. To overcome these problems, a new simple two-phase inverter voltage space vector look-up table is developed. Simulated and experimental results are presented to illustrate the validity and effectiveness of the DTC of a BLDC motor drive in the constant torque region.

II. DIRECT TORQUE CONTROL OF BLDC MOTOR DRIVES USING TWO-PHASE CONDUCTION MODE

The key issue in the DTC of a BLDC motor drive in the constant torque region is to estimate the electromagnetic torque correctly. For a surface-mounted BLDC motor the back-EMF waveform is non-sinusoidal (trapezoidal), irrelevant to conducting mode (two or three-phase), therefore (1) which is given in the stationary reference frame should be used for the electromagnetic torque calculation [6, 8].

$$T_{em} = \frac{3}{2} \frac{P}{2} \left[\frac{d\varphi_{r\alpha}}{d\theta_e} i_{s\alpha} + \frac{d\varphi_{r\beta}}{d\theta_e} i_{s\beta} \right] = \frac{3}{2} \frac{P}{2} \left[\frac{e_\alpha}{\omega_e} i_{s\alpha} + \frac{e_\beta}{\omega_e} i_{s\beta} \right] \quad (1)$$

where P is the number of poles, θ_e is the electrical rotor angle, ω_e is the electrical rotor speed, and $\varphi_{r\alpha}$, $\varphi_{r\beta}$, e_α , e_β , $i_{s\alpha}$, $i_{s\beta}$ are the stationary reference frame ($\alpha\beta$ -axes) rotor flux linkages, motor back-EMFs, and stator currents, respectively.

$$\begin{aligned} V_{s\alpha} &= R_s i_{s\alpha} + L_s \frac{di_{s\alpha}}{dt} + \frac{d\varphi_{r\alpha}}{dt} \\ V_{s\beta} &= R_s i_{s\beta} + L_s \frac{di_{s\beta}}{dt} + \frac{d\varphi_{r\beta}}{dt} \end{aligned} \quad (2)$$

Given the $\alpha\beta$ -axes the machine equations in (2) where $V_{s\alpha}$, $V_{s\beta}$, R_s , and L_s are the $\alpha\beta$ -axes stator voltages, phase resistance and inductance, respectively, the $\alpha\beta$ -axes rotor flux linkages $\varphi_{r\alpha}$ and $\varphi_{r\beta}$ are obtained by taking the integral of both sides of (2) as follows:

$$\begin{aligned} \varphi_{s\alpha} - L_s i_{s\alpha} &= \varphi_{r\alpha} \\ \varphi_{s\beta} - L_s i_{s\beta} &= \varphi_{r\beta} \end{aligned} \quad (3)$$

where $\varphi_{s\alpha}$ and $\varphi_{s\beta}$ are the α - and β -axis stator flux linkages, respectively. A BLDC motor is operated ideally when the phase current is injected at the flat top portion of the phase-to-neutral back-EMF. The back-EMF is usually flat for 120 electrical degrees and in transition for 60 electrical degrees during each half cycle. In the constant torque region (below base speed) when the phase-to-phase back-EMF voltage is smaller than the dc bus voltage there is no reason to change the amplitude of stator flux linkage. Above base speed, however, the motor performance will significantly deteriorate because the back-EMF exceeds the dc bus voltage, and the stator inductance X_s will not allow the phase current to develop quickly enough to catch up to the flat top of the trapezoidal back-EMF. Beyond the base speed, the desired torque cannot be achieved unless other techniques such as phase advancing, 180 degree conduction, etc [9] are used. Operation of the DTC of a BLDC motor above the base speed is not in the scope of this paper.

Conventional two-phase conduction quasi-square wave current control causes the locus of the stator flux linkage to be unintentionally kept in hexagonal shape if the unexcited open-phase back-EMF effect and the free-wheeling diodes are neglected, as shown in Fig. 1 with dashed lines. If the free-wheeling diode effect which is caused by commutation is ignored, more circular flux trajectory can be obtained similar to a PMSM drive. Removal of the free-wheeling diode effect on flux locus can be represented with unloaded condition, as shown in Fig. 4.

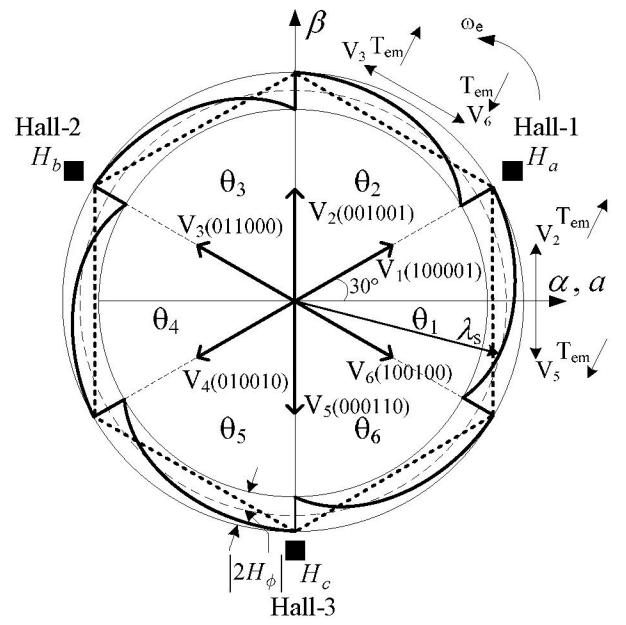


Fig. 1. Actual and ideal (dashed-line) stator flux linkage trajectories, representation of two-phase voltage space vectors, and placement of the three hall-effect sensors in the stationary $\alpha\beta$ -axes reference frame.

It has also been observed from the stator flux linkage trajectory that when conventional two-phase PWM current control is used, sharp dips occur every 60 electrical degrees. This is due to the operation of the freewheeling diodes. The same phenomenon has been noticed when the DTC scheme for a BLDC motor is used, as shown in Fig. 1 with straight lines. Due to the sharp dips in the stator flux linkage space vector at every commutation and the tendency of the currents to match with the flat top part of the phase back-EMF for smooth torque generation, there is no easy way to control the stator flux linkage amplitude. On the other hand, rotational speed of the stator flux linkage can be easily controlled, therefore fast torque response is obtained. The size of the sharp dips is quite unpredictable and depends on several factors which will be explained in the later part of this section and the related simulations are provided in the Section III. The best way to control the stator flux linkage amplitude is to know the exact shape of it, but it is considered too cumbersome in the constant torque region. Therefore, in the DTC of a BLDC motor drive with two-phase conduction scheme, the flux error φ in the voltage vector selection look-up table is always selected as zero and only the torque error τ is used depending on the error level of the actual torque from the reference torque. If the reference torque is bigger than the actual torque, within the hysteresis bandwidth, the torque error τ is defined as "1," otherwise it is "-1," as shown in Table I.

A. Control of Electromagnetic Torque by Selecting the Proper Stator Voltage Space Vector

A change in the torque can be achieved by keeping the amplitude of the stator flux linkage constant and increasing the rotational speed of the stator flux linkage as fast as possible. This allows a fast torque response to be achieved. It is shown in this section that the rotational speed of the stator flux linkage can be controlled by selecting the proper voltage vectors while keeping the flux amplitude almost constant, in other words eliminating the flux control.

When the primary windings, which are assumed to be symmetric fed by an inverter using two-phase conduction mode, as shown in Fig. 2, the primary voltages, V_{an} , V_{bn} , and V_{cn} , are determined by the status of the six switches: SW_1 , SW_2 , ..., and SW_6 . For example, if SW_1 is one (turned on) and SW_2 is zero (turned off) then $V_{an} = V_{dc}/2$ and similarly for V_{bn} and V_{cn} . Since the upper and lower switches in a phase leg may both be simultaneously off, irrespective of the state of the associated freewheeling diodes in two-phase conduction mode, six digits are required for the inverter operation, one digit for each switch [6]. Therefore, there is a total of six non-zero voltage vectors and a zero voltage vector for the two-phase conduction mode which can be represented as $V_{0,1,2,\dots,6}$ (SW_1 , SW_2 , ..., SW_6), as shown in Fig. 1. The six nonzero vectors are 60 degrees electrically apart from each other, as depicted in Fig. 1, but 30 electrical degrees phase shifted from the

corresponding three-phase voltage vectors which are used in DTC of a PMSM drive. The overall block diagram of the closed-loop DTC scheme of a BLDC motor drive in the constant torque region is represented in Fig. 3. The grey area represents the stator flux linkage control part of the scheme used only for comparison purposes. When the two switches in Fig. 3 are changed from state 2 to state 1, flux control is considered in the overall system along with torque control. In the two-phase conduction mode the shape of stator flux linkage trajectory is ideally expected to be hexagonal, as illustrated with dashed-lines in Fig. 1. However, the influence of the unexcited open-phase back-EMF causes each straight side of the ideal hexagonal shape of the stator flux linkage locus to be curved and the actual stator flux linkage trajectory tends to be more circular in shape, as shown in Fig. 1 with straight lines [6]. In addition to the sharp changes, curved shape in the flux locus between two consecutive commutations complicates the control of the stator flux linkage amplitude because it depends on the size of the sharp dips and the depth of the change may vary with sampling time, dc-link voltage, hysteresis bandwidth, motor parameters especially the phase inductance, motor speed, snubber circuit, and the amount of load torque.

If a BLDC motor has an ideal trapezoidal back-EMF having a 120 electrical degree flat top, one current sensor on the dc-link can be used to estimate the torque. By knowing the sectors using hall-effect sensors the torque can be estimated with $T_{em} = 2k_e i_{dc}$, where k_e is the back-EMF constant and i_{dc} is the dc-link current. In reality, this might generate some low-frequency torque oscillations due to the approximation of the back-EMF as ideal trapezoid. To achieve a more accurate torque estimation, in general, for non-sinusoidal surface-mounted permanent magnet motors it is suggested that (1) should be used.

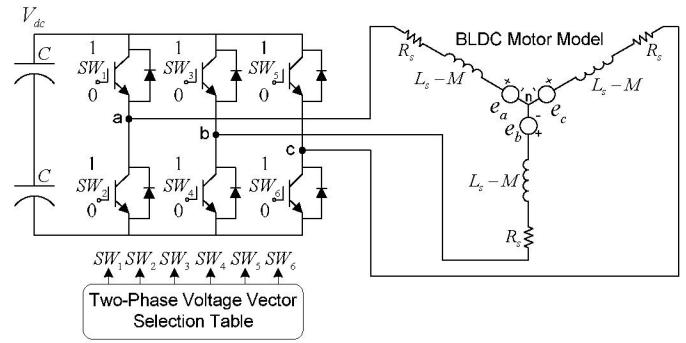


Fig. 2. Representation of two-phase switching states of the inverter voltage space vectors for a BLDC motor.

Usually the overall control system of a BLDC motor drive includes three hall-effect position sensors mounted on the stator 120 electrical degrees apart. These are used to provide low ripple torque control if the back-EMF is ideally trapezoidal because current commutation occurs only every 60 electrical degrees, as shown in Fig. 1. Nevertheless, using high resolution position sensors is quite useful if the back-EMF of

TABLE I
TWO-PHASE VOLTAGE VECTOR SELECTION FOR BLDC MOTOR

φ	τ	θ					
		θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
1	1	$V_1(100001)$	$V_2(001001)$	$V_3(011000)$	$V_4(010010)$	$V_5(000110)$	$V_6(100100)$
	-1	$V_6(100100)$	$V_1(100001)$	$V_2(001001)$	$V_3(011000)$	$V_4(010010)$	$V_5(000110)$
0	1	$V_2(001001)$	$V_3(011000)$	$V_4(010010)$	$V_5(000110)$	$V_6(100100)$	$V_1(100001)$
	-1	$V_5(000110)$	$V_6(100100)$	$V_1(100001)$	$V_2(001001)$	$V_3(011000)$	$V_4(010010)$
-1	1	$V_3(011000)$	$V_4(010010)$	$V_5(000110)$	$V_6(100100)$	$V_1(100001)$	$V_2(001001)$
	-1	$V_4(010010)$	$V_5(000110)$	$V_6(100100)$	$V_1(100001)$	$V_2(001001)$	$V_3(011000)$

Note: The italic grey area is not used in the proposed DTC of a BLDC motor drive.

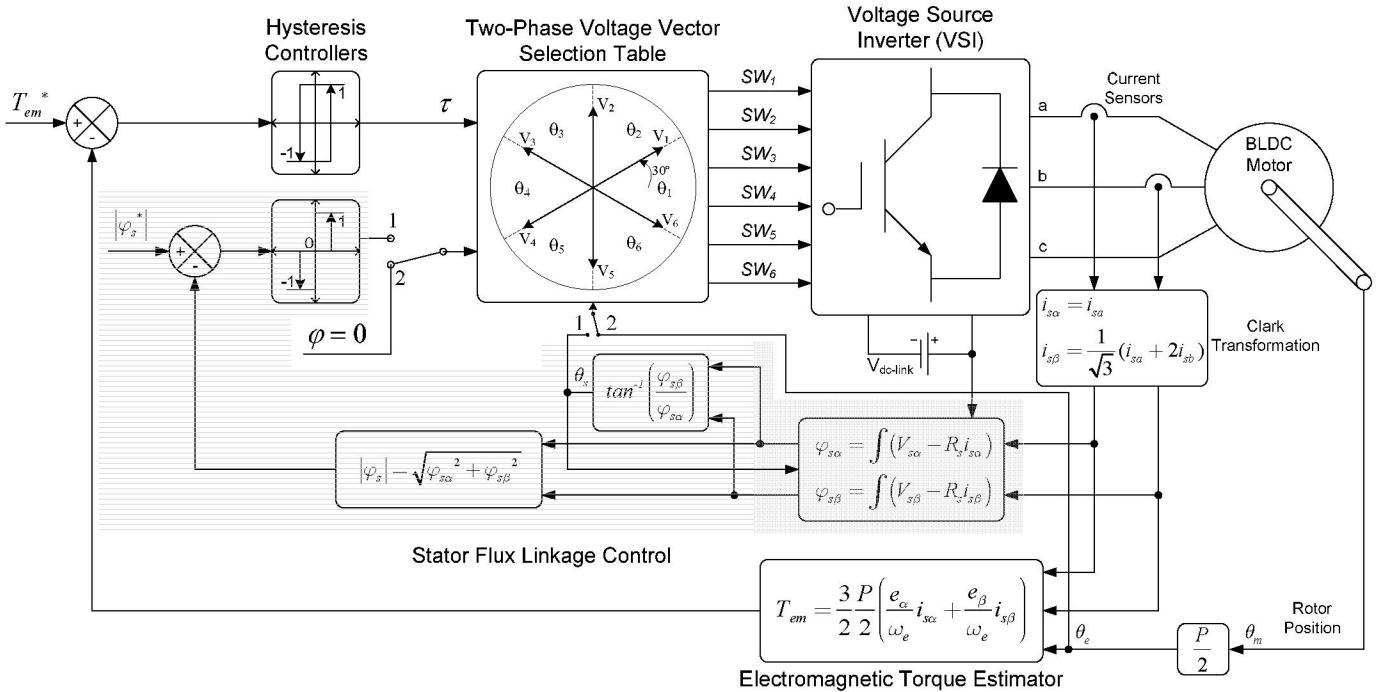


Fig. 3. Overall block diagram of the two-phase conduction DTC of a BLDC motor drive in the constant torque region.

BLDC motor is not ideally trapezoidal. The derivative of the rotor $\alpha\beta$ -axes fluxes obtained from (3) over electrical position, which is described in (1), will cause problems mainly due to the sharp dips at every commutation point. The $\alpha\beta$ -axes motor back-EMFs e_α and e_β vs. electrical rotor position θ_e values can be created in the look-up table, respectively with great precision depending on the resolution of the position sensor (for example incremental encoder with 2048 pulses/revolution), therefore very accurate $\alpha\beta$ -axes back-EMF values and eventually a good torque estimation can be obtained.

III. SIMULATION RESULTS

The drive system shown in Fig. 3 has been simulated for various cases with and without stator flux control, switch states 1 and 2, respectively in order to demonstrate the validity of the

proposed two-phase conduction DTC of a BLDC motor drive scheme.

To set the gating signals of the power switches easily and represent the real conditions in simulation as close as possible the electrical model of the actual BLDC motor with R-L elements and the inverter with power semiconductor switches considering the snubber circuit are designed in Matlab/Simulink® using the SimPower Systems toolbox.

The dead-time of the inverter and non ideal effects of the BLDC machine are neglected in the simulation model. The sampling interval is 25 μ s. The switching table, which is given in Table I is employed for the proposed DTC of the BLDC motor drive. The magnitudes of the torque and flux hysteresis bands are 0.001 N·m, and 0.001 Wb, respectively. It may be noted that the zero voltage vector suggested in [6] is not used in the proposed scheme due to the reasons explained in Section I.

Figs. 4 and 5 show the simulation results of the uncontrolled open-loop stator flux linkage locus when 0 N·m and 1.2835 N·m load torque are applied to the BLDC motor with ideal trapezoidal back-EMF, respectively. Steady-state speed control is performed with an inner-loop torque control without flux control. Stator flux linkage is estimated using (1) as an open-loop. As can be seen in Fig. 5 when the load torque level increases, more deep sharp changes are observed which increases the difficulty of the flux control if it is used in the control scheme. The steady-state speed is 30 mechanical rad/s and the dc-link voltage V_{dc} equals 33.94 V. Since the speed is controlled a better open-loop circular flux trajectory is obtained.

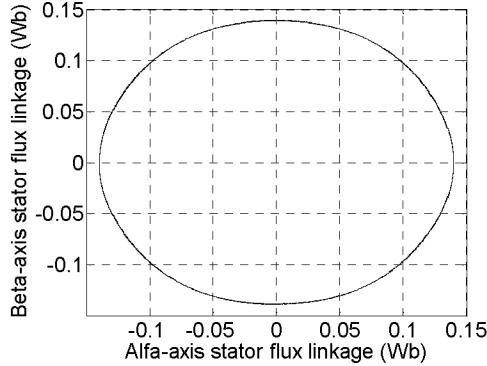


Fig. 4. Simulated open-loop stator flux linkage trajectory under the two-phase conduction DTC of a BLDC motor drive at no load torque (speed + torque control).

Under only torque control, when the zero voltage vector V_0 is used to decrease the torque, as suggested in [6], larger, more frequent spikes on the phase voltages are observed than that of the ones used from the suggested voltage vector look-up table given in Table I, as shown in Fig. 6.

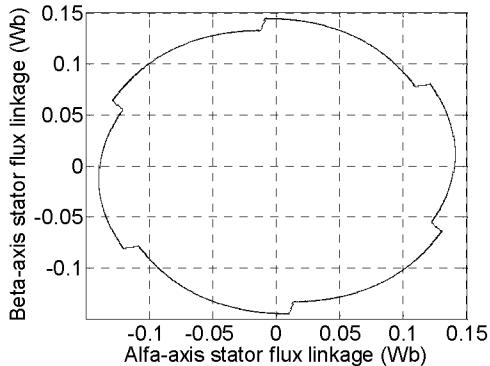


Fig. 5. Simulated open-loop stator flux linkage trajectory under the two-phase conduction DTC of a BLDC motor drive at 1.2835 N·m load torque (speed + torque control).

Using the actual $\alpha\beta$ -axes motor back-EMFs obtained in (3) looks like the best solution for a good stator flux reference similar to the DTC of a PMSM drive. Unlike BLDC motor, in PMSM since both α - and β -axis motor back-EMFs are in sinusoidal shape, constant stator flux linkage amplitude is

obtained. However, for BLDC motor, unexcited open-phase back-EMF effect on flux locus and more importantly the size of the sharp dips cannot easily be predicted to achieve a good stator flux reference in two-phase conduction mode. Fig. 7 represents the reference stator flux locus obtained in (3) when back-EMF is not ideally a trapezoidal under full-load (1.2835 N·m). The simulation time is 3 seconds. Due to the distorted voltage and current, the stator flux locus drifts considerably as can be seen in Fig. 7.

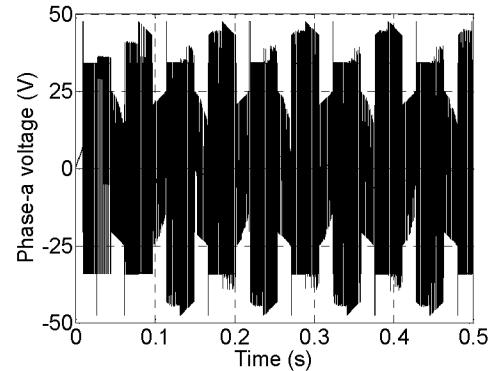


Fig. 6. Simulated phase-a voltage under 1.2 N·m load when zero voltage vector is used to decrease the torque (only torque control is performed).

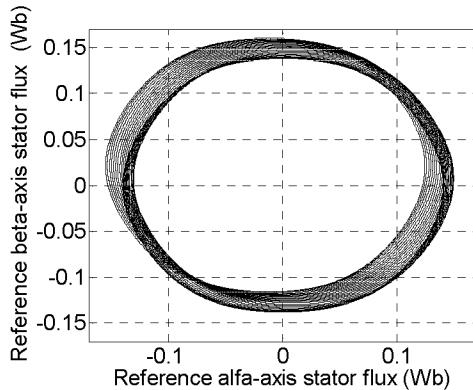


Fig. 7. Simulated reference stator flux linkage locus using actual $\alpha\beta$ -axes back-EMF from (3) under full load (speed + torque + flux control).

Even though the torque control still exist for some time with low-frequency oscillations, motor will be damaged because of high terminal current exceeding the peak current of 24 A, as shown in Fig. 8. Instability in the torque compared to the current does not occur except high ripples because speed control corrects the errors in the torque by applying unwanted amount of voltage. There is higher voltage than what is expected (~ 34 V) in the motor terminals compared to when just torque control is used without flux control. Because large and distorted terminal voltages exist, higher and distorted phase currents as seen in Fig. 8 are obvious. All these problems are because of the flux control. There should be exact flux amplitude to be given as a reference flux value including sharp changes at every commutation points and curved shape between those commutation points, then appropriate flux

control can be obtained without losing the torque control. However, to predict all these circumstances to generate a flux reference is cumbersome work which is unnecessary in the constant torque region.

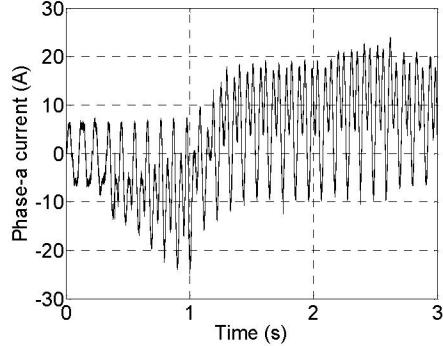


Fig. 8. Simulated phase-a current when flux control is obtained using (3) under full load (speed + torque + flux control).

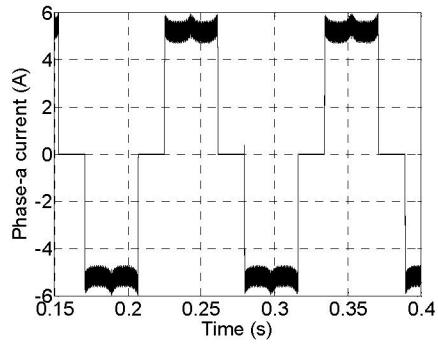


Fig. 9. Simulated phase-a current when just torque is controlled without flux control under 1.2 N·m load with non-ideal trapezoidal back-EMF (reference torque is 1.225 N·m).

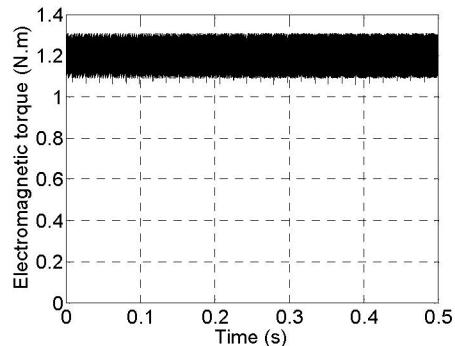


Fig. 10. Simulated electromagnetic torque when just torque is controlled without flux control under 1.2 N·m load with non-ideal trapezoidal back-EMF (reference torque is 1.225 N·m).

Figs. 9-11 show phase-a current, electromagnetic torque and phase-a voltage, respectively under only torque control when the back-EMF is not ideally trapezoidal considering only the first, third and fifth harmonics of the fundamental ideal trapezoidal back-EMF. Reference torque is 1.225 N·m and the load torque is 1.2 N·m, thereby speed is kept at around 55 electrical rad/s for a better circular flux locus. If high resolution position sensor such as incremental encoder is used instead of the three hall-effect sensors, low-frequency torque

oscillations can be minimized by using (1), as shown in Fig. 10.

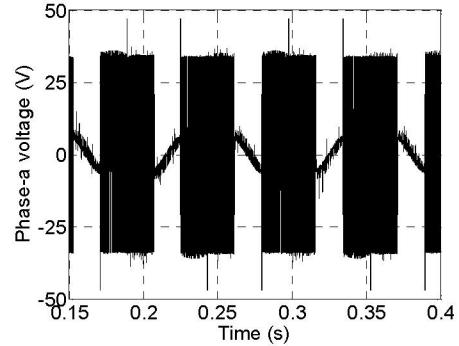


Fig. 11. Simulated phase-a voltage when just torque is controlled without flux control under 1.2 N·m load with non-ideal trapezoidal back-EMF (reference torque is 1.225 N·m).

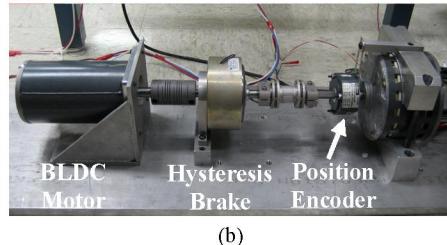
In (1), the exact shapes of phase back-EMFs are obtained offline and transformed to $\alpha\beta$ -axes. Thus, the product of the real back-EMF values by the corresponding $\alpha\beta$ -axes currents, number of pole pairs, and inverse speed provide the exact values of the α - and β -axis torque, respectively.

IV. EXPERIMENTAL RESULTS

The feasibility and practical features of the proposed DTC scheme of a BLDC motor drive have been evaluated using an experimental test-bed, as shown in Fig. 12. The proposed control algorithm is digitally implemented using the eZdspTM board from Spectrum Digital, Inc. based on TMS320F2812 DSP, as shown in Fig. 12(a). In Fig. 12(b), the BLDC motor whose parameters are given in the Appendix is coupled to the overall system.



(a)



(b)

Fig. 12. Experimental test-bed. (a) Inverter and DSP control unit. (b) BLDC motor coupled to dynamometer and position encoder (2048 pulse/rev).

In this section, transient and steady-state torque and current responses of the proposed two-phase conduction DTC scheme of a BLDC motor drive are demonstrated experimentally under 0.2 pu load torque condition. The experimental results are obtained from the datalog (data logging) module in the Texas Instruments Code Composer StudioTM IDE software.

Fig. 13(a) and (b) illustrate the experimental results of the phase-a current and torque, respectively when only torque control is performed using (1), as shown in Fig. 3 with switch state 1. In Fig. 13(b), the reference torque is suddenly increased from 0.225 pu to 0.45 pu at 9.4 ms under 0.2 pu load torque. One per-unit is 1.146 N·m for torque, 5 A for current, and 1800 rpm for speed. The sampling time is chosen as 1/30000 second, hysteresis bandwidth is 0.001 N·m, dead-time compensation is included, and the dc-link voltage is set to $V_{dc} = 33.94$ V. As it can be seen in Fig. 13(a) and (b), when the torque is suddenly increased the current amplitude also increases and fast torque response is achieved. The high frequency ripples observed in the torque and current are related to the sampling time, hysteresis bandwidth, winding inductance, and dc-link voltage. This is well in accordance with the simulation results in Figs. 9-11 where the sampling time is chosen as 25 μ s.

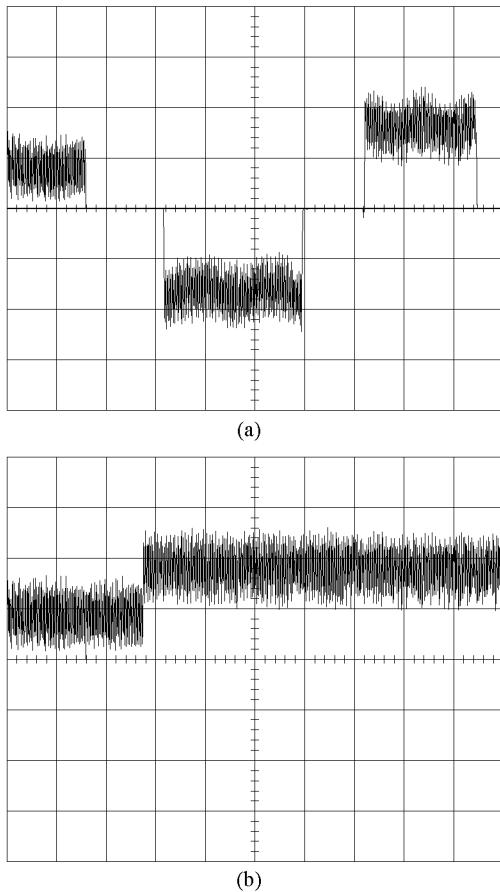


Fig. 13. (a) Experimental phase-a current (0.25 pu/div) and (b) electromagnetic torque in per-unit under 0.2 pu load torque (0.25 pu/div). Time base: 3.4 ms/div.

V. CONCLUSION

This study has successfully demonstrated application of the proposed two-phase conduction direct torque control (DTC) scheme for BLDC motor drives in the constant torque region. 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, this approach eliminates the flux control and only torque is considered in the overall control system. Three reasons are given for eliminating the flux control. First, since the line-to-line back-EMF including the small voltage drops is less than the dc-link voltage in the constant torque region there is no need to control the flux amplitude. Second, with the two-phase conduction mode sudden sharp dips in the stator flux linkage locus occur that complicate the control scheme. The size of these sharp dips is unpredictable. Third, regardless of the stator flux linkage amplitude, the phase currents tend to match with the flat top portion of the corresponding trapezoidal back-EMF to generate constant torque.

APPENDIX

SPECIFICATIONS AND PARAMETERS OF THE BLDC MOTOR

Symbol	Quantity	Value
P	Number of poles	4
V_{LL}	Maximum line-to-line voltage (V _{rms})	115
I_{pk}	Maximum peak current (A)	24
I_{rated}	Rated current (A)	5.6
T_{rated}	Rated torque (N·m)	1.28352
L_s	Winding inductance (mH)	1.4
M	Mutual inductance (mH)	0.3125
R_s	Winding resistance (ohm)	0.315
λ_f	Rotor magnetic flux linkage (Wb)	0.1146

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