Engineering Science and Technology, an International Journal xxx (2017) xxx–xxx

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Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: www.elsevier.com/locate/jestch

Full Length Article

A simple overlap angle control strategy for reducing commutation torque ripple in a brushless DC motor drive

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A R T I C L E I N F O

Article history:
Received 25 February 2017
Revised 19 September 2017
Accepted 22 September 2017
Available online xxxx

Keywords:
Commutation torque ripple
brushless DC motor
Direct torque control
Twelve voltage space vector
Overlap angle control, inverter losses

A B S T R A C T

A commutation torque ripple is generated in a brushless DC motor due to a finite time taken for current transfer between outgoing phase and incoming phase due to the phase inductance. The effect of commutation ripple will be more severe for low voltage high current BLDC drives used for automotive applications. Direct Torque Control (DTC) techniques are used to reduce the torque ripple. Two phase conduction with six voltage space vectors and three phase conduction with twelve voltage space vectors with DTC are used to reduce the torque ripple. Twelve Step DTC (TSDTC) is capable of reducing torque ripple considerably but at the cost of increased inverter and winding losses. In Six Step DTC (SSDTC) the torque ripple is higher than that of TSDTC but with reduced winding and inverter losses. In this paper an attempt has been made to strike a balance between torque ripple and losses. A novel Direct Torque Control with twelve voltage space vector with overlap angle control has been proposed. The proposed method is validated through simulation and experimental results.

1. Introduction

Brushless DC (BLDC) motors are widely used due to their advantages such as better power/weight and torque/current ratio compared to Permanent Magnet Synchronous Motor (PMSM) [1]. The torque ripple is mainly due to Pulse Width Modulation (PWM), non-ideal trapezoidal back-EMF and commutation between outgoing and incoming phases [2]. Torque ripple due to PWM can be taken care of by the rotor inertia but the commutation torque ripple is greater in magnitude and severely affects the motor performance. Commutation torque ripple is due to finite transition time between outgoing phase current to incoming phase current due to winding inductance [3,4]. The commutation torque ripple produces adverse effect, reduces reliability of the BLDC drive and the relevant studies are reported in [3–5]. Various current control techniques are used to minimize torque ripple, by deriving shape function [2], controlling DC link current [2] and controlling common DC signal current [6]. An attempt has been made by Song and Choy to control commutation torque ripple by using DC link current as discussed [7]. In the above work the time-derivative of outgoing and incoming phase current is utilized to calculate duty ratio to control commutation interval. The effect of DC link voltage, back-EMF and phase current on commutation is analysed in [8]. It has been stated that when phase back-EMF is higher than one fourth of the DC link voltage the control in phase current cannot compensate effect on torque pulsation during commutation. The generation of torque ripple during phase commutation is mathematically analysed in [9,10]. The influence of commutation time on torque ripple and the relation between commutation time and speed have been analysed. The commutation time is determined using detection and comparator circuits. The commutation torque ripple reduction using PWM techniques and without using commutation time calculation is discussed in [11]. A control strategy for speed control of SRM drive along with torque ripple reduction has been proposed in [12]. Minimization in torque ripple is attempted by controlling current profile and by selecting suitable turn on and turn off angles. The effect of hybrid switching conduction on commutation torque ripple for 120° and 180° conduction mode has been analysed in [13] for various operating speeds. The idea to equalize the mismatched time of two commutating phase currents during commutation interval is discussed and analysed in [14] for low and high speed motor operation. The detailed analysis of commutation torque ripple due to phase current is presented in [15]. It has been concluded that the commutation torque ripple is not only dependent on variation in current but also on increase in speed. In [16], the detailed expressions of variation in torque under non-commutation and commutation period have been deduced. The torque variation rate is analysed and the opti-

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Peer review under responsibility of Karabuk University.

https://doi.org/10.1016/j.jestch.2017.09.005
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Please cite this article in press as: C.K. Lad, R. Chudamani, A simple overlap angle control strategy for reducing commutation torque ripple in a brushless DC motor drive, Eng. Sci. Tech., Int. J. (2017), https://doi.org/10.1016/j.jestch.2017.09.005

mization in switching vector selection is discussed based on sign of variation in torque ripple to reduce commutation torque ripple and torque ripple due to non-ideal back-EMF. The method has been proposed in [17] to measure commutation interval from terminal voltage and to calculate pwm duty ratio to suppress commutation torque ripple. Lu et al. proposed a method to reduce torque ripple of BLDC motor with nonideal back EMF [18] based on duty ratio calculation by ignoring diode freewheeling of the inactive phase. Several works have been reported regarding commutation torque ripple.

The direct torque control (DTC) emerged as a solution for these problems and it was originally developed for the control of induction motor drives in which direct control of flux and electromagnetic torque was attempted. It utilized the estimated flux and electromagnetic torque to derive optimal inverter switching to obtain fast response. The DTC for PMSM has been introduced in [19]. The DTC of BLDC motor differs from that of the induction motor and PMSM due to non-sinusoidal back-EMF. Based on the characteristics of BLDC, the hybrid conduction mode is introduced to reduce torque ripple in [20,21]. For direct torque control it is important that the estimated torque is accurate. The direct self controlled method for BLDC by utilizing stator flux linkage reference with three phase conduction is discussed in [22]. The rounding effect in phase back-EMF is one of the cause for torque ripple production, the back-EMF is derived by using shape function in [23] for torque estimation.

The DTC scheme for BLDC motor drives to reduce low-frequency torque ripple and obtain fast torque response is discussed in [21]. It has been observed that there are dips in flux amplitude at every 60 electrical degrees due to commutation. The effect of applying zero voltage space vector in DTC of permanent magnet machine is not same as that in induction motor. It is due to the effect of permanent magnet and is discussed by Zhong and Rahman in [19]. Since magnets are rotating, the vector of stator flux linkage will change even when the zero voltage vectors are selected. Thus the stator flux linkage vector in a permanent magnet motor cannot be controlled by the zero voltage vector. It is discussed in [24] that the use of zero voltage vector decreases the torque slowly in permanent magnet motor compared to induction motor. The DTC of BLDC motor by using accelerating-decelerating vectors is suggested by Ozturk and Toliyat in [25]. The DTC using 12 voltage space vector for alternate two and three phase conduction is discussed in [26]. Though torque ripple is controlled in this method, switching losses in the inverter and winding losses are increased. Torque ripple reduction by using three level hysteresis torque controller is discussed in [27]. The use of three level hysteresis controller results into a complex algorithm for selecting the vectors that are to be switched.

The torque ripple is appreciably high with six voltage space vector and two phase conduction and it is reduced by using twelve voltage space vectors but at the cost of increased inverter and winding losses. In three phase conduction control method the duration for which three switches conduct simultaneously is 30 electrical degrees. This duration of three phase conduction is called overlap region and it is given by $2\theta_{ov}$ where θ_{ov} is the overlap angle. Keeping the overlap angle ‘ θ_{ov} ’ equal for all load currents in TSDTC, results in increased inverter and winding losses. An attempt has been made to reduce torque ripple as well as inverter and winding losses by choosing ‘ θ_{ov} ’ as a function of load and speed.

In this paper a Direct Torque Control technique to reduce the commutation torque ripple has been proposed. This method is essentially the twelve voltage space vector technique with overlap angle control. Conduction of three devices simultaneously for fixed duration of 30° in-between two consecutive sectors of 60° is discussed in [26] to reduce commutation torque ripple. An attempt has been made in this work for reducing the commutation torque ripple but at the same time trying to reduce the conduction period of three devices to limit the inverter and winding losses. In the proposed method the duration for which three devices conduct simultaneously is not fixed but varies with speed and load. The overlap angle is determined using lookup table based on speed and load. In this paper for the convenience of explanation, two phase conduction DTC using six switching space vector has been abbreviated as SSDTC (Six Step DTC) and combined two phase - three phase conduction DTC using twelve switching space vector as TSDTC (Twelve Step DTC). The performance of the drive for the proposed method is analysed with various load conditions and the results are presented.

2. Proposed DTC with overlap angle control

BLDC motor is basically operated in two phase conduction mode, but with two phase conduction commutation torque ripple is produced during transition between incoming phase and outgoing phase. During commutation, transient torque is developed because the sum of the two commutating current is rarely constant. If back-EMFs are assumed constant and equal in magnitude, as well as speed of the motor is assumed to be constant then the pulsating torque will be zero if,

$$|i_b + i_c| = i_a = I_{av} \tag{1}$$

Unfortunately due to winding inductance, the sum of commutating current is never constant and hence commutation ripple is produced. The commutation torque ripple can be reduced by maintaining the sum of the current from outgoing phase to incoming phase constant and equal to I_{av}. This can be achieved by three phase conduction of BLDC motor during commutation. The adverse effect of commutation is observed on motor performance when the motor is fully loaded and run at high speed. The TSDTC method discussed in [26] to reduce commutation torque ripple uses alternately two and three phase conduction. The switching losses in the inverter are more as three phases are switched on simultaneously for 30° irrespective of load. Also the copper losses in the winding are higher due to increase in phase conduction to 150° compared to 120° in SSDTC. In the proposed method the drive is operated in the three phase conduction only for duration of $2\theta_{ov}$ where θ_{ov} is the overlap angle and it varies with speed and load. It is low for lightly loaded and low/medium speed condition; the operation is more close to SSDTC with reduced torque ripple.

The schematic diagram of the proposed method of DTC of BLDC is shown in Fig. 1. The proposed method is implemented in the following sequence: (i) flux linkage estimation (ii) torque estimation (iii) determination of overlap angle ‘θ_{ov}’ (iv) identification of overlap and non-overlap region using θ_{ov} (v) selection of switching space vector. These are explained in subsequent sub-sections.

2.1. Flux linkage estimation for BLDC drive

The phase back-EMF cannot be easily obtained in a BLDC motor due to non availability of neutral terminal. Thus line-to-line terminal voltages are utilized to determine $v_{s\alpha}$ and $v_{s\beta}$ using Clarke transformation. The line-to-line Clarke transformation to obtain $v_{s\alpha\beta}$ from $v_{ab-bc-ca}$ is derived from Fig. 2 using Eqs. (2)–(6).

$$v_{s\alpha} = \frac{2}{3\sqrt{3}}[v_{ab}\cos 30^\circ - v_{ca}\cos 30^\circ] \tag{2}$$

$$v_{s\alpha} = \frac{1}{3\sqrt{3}}[\sqrt{3}v_{ab} - \sqrt{3}v_{ca}] \tag{3}$$

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