역기전력을 고려 한 브러시레스 전동기의 토크리플 저감에 관한 구동 방식에 대한 연구

손도, 남기용, 이근호, 홍정표
창원대학교 전기공학과

A Torque Ripple Reduction Drive Strategy for Permanent Magnet Brushless DC Motor with Imperfect Back Electromotive Force

Tao Sun, Gi-Yong Nam, Geun-Ho Lee, Jung-Pyo Hong
Changwon National University

Abstract - This paper presents a drive strategy to reduce torque ripple of a permanent magnet Brushless DC Motor (BLDCM) with short 120^0 flat top Back Electromotive Force (Back-EMF). In this strategy, the phase Back-EMF is divided into four sections. Then, in each section the phase current is regulated by corresponding PWM duty ratio to compensatethe torque ripple caused by imperfect Back-EMF. A program based on this strategy has been implemented in MATLAB@Simulink. The validity of the presented method is verified by simulation results.

1. Introduction

In BLDCM drive, the commutation process may produce a current ripple in the non-commutated phase. In ideal Back-EMF case, it directly causes a ripple in torque [1]. Many analysis and solutions have been introduced to reduce the commutation current ripple such as [2] and [3]. In practice, however, the Back-EMF usually has an imperfect short 120^0 flat top as shown in Fig. 1 (a). According to the conventional solutions, the torque for this imperfect Back-EMF is simulated and shown in Fig. 1 (b). Because the torque ripple gets about 30% of mean torque value, the conventional solutions are valid no more.

In this paper, a strategy of torque ripple reduction for the BLDCM with imperfect Back-EMF is presented. In this strategy, the Back-EMF per 60^0 is divided into four sections. Then, in each section the phase current is regulated by corresponding PWM duty-ratio to reduce the torque ripple caused by imperfect Back-EMF. In addition, for imperfect Back-EMF, a new criterion to estimate torque ripple during phase commutations proposed. A program based on this strategy and table 1 parameters has been implemented in MATLAB@Simulink. The validity of the presented method is verified by simulation results.

2. Proposed Solution

The assumption of 3-phase BLDCM stator windings is "Y" connected. The inverter and motor equivalent circuit is shown in Fig. 2 (a) According to it, the dynamic equations of a BLDCM can be expressed in (1) and (2).

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} + \begin{bmatrix} V_{nn0} \\ V_{nn0} \\ V_{nn0} \end{bmatrix} \quad (1)$$

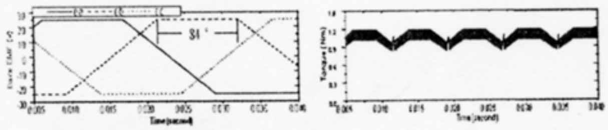
$$T = \frac{1}{\omega}(e_a i_a + e_b i_b + e_c i_c) \quad (2)$$

Because the proposed model is symmetrical, the analysis of one commutation section is also suitable for the whole period. Fig. 2 (b) shows the chosen commutation section where phase a and phase b are out-going phase and in-coming phase, respectively. On the other side, according to Back-EMF and current state, 4 sections are assumed as shown in Fig. 2 (b).

2.1 Section I

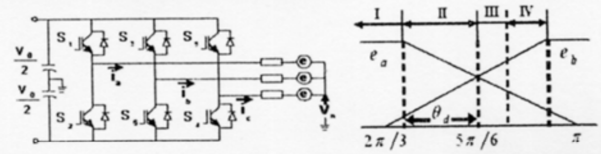
In this section, only one current flows in series connected phase a and c. In the assumption, the Back-EMFs of phase a and c are constant. Thus, the torque can be expressed as (3)

$$e_a i_a + e_c i_c = 2EI \quad (3)$$



(a) (b)

<Fig. 1> (a)the imperfect Back-EMF (b)the torque ripple caused by imperfect Back-EMF



(a) (b)

<Fig. 2> (a) the equivalent circuit of a BLDCM drive system (b)the Bakc-EMF divided into 4 sections

where E is constant value of Back-EMF, I is set-point value of phase current. A set-point torque value also is set in this section.

2.2 Section II

In section II, phase-a Back-EMF begin varying with electrical position. How to give current of each phase to be able to maintain 2EI torque is the control purpose.

According to (2), the reference current varying rate can be gotten. By means of controlling switch 1 and 2, the phase a and c current can be equated to reference current. And the State-Space Averaging Technique could be used to get a PWM duty-ratio (4) that can determine how to control the switch 1 and 2 and hence the current varying rate.

$$D_2 = \frac{2I\omega L(\pi/6+\theta_d)}{V_0(7\pi/6+\theta_d-\theta)} + \frac{E(23\pi/6-4\theta-\theta_d)}{3V_0(\pi/6+\theta_d)} + \frac{1}{2} \quad (4)$$

2.3 Section III

Owing to the position sensor, the phase b is triggered from this section, which is the beginning of commutation. Until phase-a current vanishes, the commutation process finishes. Usually, the commutation duration is so short that the Back-EMFs can be regarded as constant. Hence, the drive strategy in this section focuses on current ripple directly. And according to (2), the reference current varying rate is gotten as

$$\frac{di_b}{dt} = (-\frac{di_a}{dt}) \Rightarrow \frac{V_0}{E} = \frac{4\pi+12\theta_d}{\pi+6\theta_d} \quad \text{(case 1)} \quad (5)$$

$$\frac{di_b}{dt} > (-\frac{di_a}{dt}) \Rightarrow \frac{V_0}{E} > \frac{4\pi+12\theta_d}{\pi+6\theta_d} \quad \text{(case 2)} \quad (6)$$

$$\frac{di_b}{dt} < (-\frac{di_a}{dt}) \Rightarrow \frac{V_0}{E} < \frac{4\pi+12\theta_d}{\pi+6\theta_d} \quad \text{(case 3)} \quad (7)$$

Case 1 shows that there is no torque ripple in section III if the ratio of DC-Link voltage and phase Back-EMF constant value is same to (5). This is also a new criterion for the BLDCM with imperfect Back-EMF to estimate the commutation torque ripple state, whereas Case 2 and Case 3 mean that there are spike current ripple and dip current ripple respectively during commutation.

In order to reduce the current ripple of case 2 and case 3, the in-coming or out-going phase should be controlled by corresponding PWM. For the case 2, the PWM duty-ratio for controlling phase-b current is

$$D_{31} = \frac{2}{3} + \frac{4E(\pi + 3\theta_d)}{3V_0(\pi + 6\theta_d)} \tag{8}$$

In order to reduce the current ripple of case 3, the out-going phase (phase a) is controlled by PWM. It is somewhat different from the last control strategy because that controlling of phase a can affect phase-b current due to neutral voltage as shown in (9)

$$V_{nn0} = -\frac{V_0 S_{32}}{6} - \frac{e_a + e_b + e_c}{3} \tag{9}$$

Hence, the duty ratio for reducing the dip current ripple of case 3 in commutation step is

$$D_{32} = 2 - \frac{2E(2\pi + 6\theta_d)}{V_0(\pi + 6\theta_d)} \tag{10}$$

2.4 Section IV

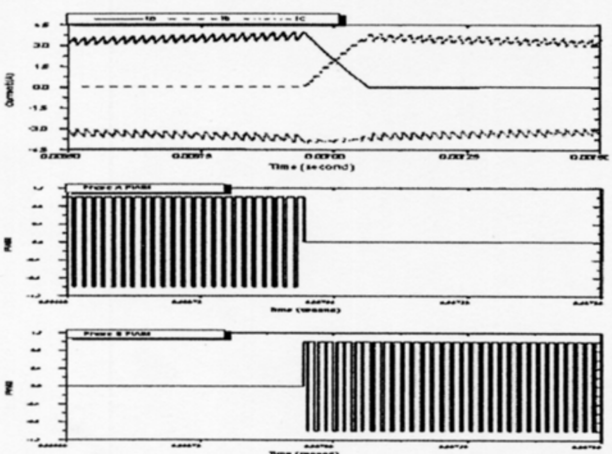
When phase-a current vanishes, the commutation step finishes. But phase-b Back-EMF still is in varying state, which is similar to the phase-a Back-EMF in section II. In the same method with section II, the corresponding PWM duty-ratio is

$$D_4 = \frac{2IL\omega(\pi/6 + \theta_d)}{V_0(\theta + \theta_d - \pi/2)^2} + E\frac{2\theta + \theta_d - 7\pi/6}{3V_0(\pi/6 + \theta_d)} + \frac{1}{2} \tag{11}$$

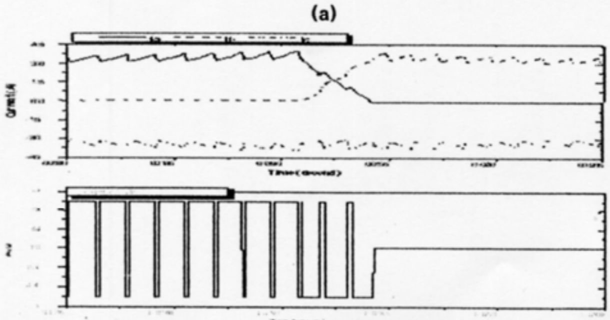
3. Simulation Result

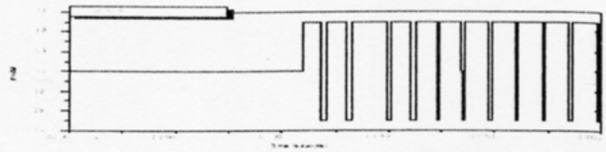
The figure 4 (a) and (b) show the simulation results and corresponding PWM that the proposed strategy is adopted to reduce case 2 and case 3 current ripples.

The current shape based on the proposed strategy is shown in figure 4 (c). And the corresponding torque whose ripple has been reduced by the proposed method is shown in figure 4 (d). It is evident that the torque ripple is reduced from about 30% to about 10% of mean value.

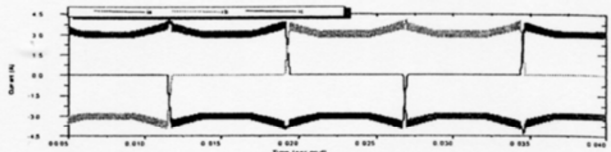


(a)

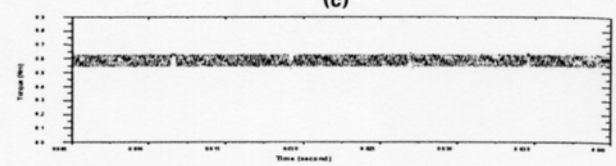




(b)



(c)



(d)

<Fig. 4> (a)the current in the proposed strategy for solving case 2 and corresponding PWM; (b)the current in the proposed strategy for solving case 3 and corrensponding PWM; (c)the 3-phase currents of the proposed strategy; (d)the improved torque by the proposed strategy

4. Conclusion

This paper presents a novel drive strategy to reduce torque ripple of BLDCM with short 120° flat top Back-EMF. In this strategy, the Back-EMF is divided into four different sections. Then, in each section the phase currents are regulated by corresponding PWM duty-ratio, which compensates the torque ripple caused by imperfect Back-EMF. Particularly, in commutation section, the conventional commutation torque ripple estimation equation is no more valid. An improved criterion is proposed in this paper. Depending on it, the commutation torque ripple can be predicted and suppressed easily. And Due to the all drive sections are mainly determined by Back-EMF shape and rotor position, the robust performance is achieved in this strategy. A program based on this strategy has been implemented in MATLAB@Simulink. The validity of the strategy has been verified by simulation results, which show the torque ripple is reduced from 30% to 10% of mean torque value.

<Table 1> Motor Parameters

DC-Link Voltage	110/81.2 (V)
Θ_d	π/10
Phase Inductance	3.05 (mH)
Phase Resistance	0.75 (Ohm)
Speed	1300 (rpm)
Back-EMF	25 (V)

본 연구는 산업자원부 지방기술혁신사업(RTI04-01-03)
지원으로 수행되었습니다

[Reference]

[1] R. Krishnan, "Electric Motor Drives - modeling, analysis, and control" ISBN 0-13-0910147, Pearson Education, Prentice Hall.

[2] T. M. Jahns and W. L. Soong, "Pulsating Torque Minimization Techniques for Permanent Magnet AC Motor Drives a Review", IEEE Transactions on Industrial Electronics, Vol. 43, No. 2, PP. 321-330, 1996

[3] Renato Carlson, Member IEEE, Michel Lajoie-Mazenc, and Joao C. dos S. Fagundes "Analysis of Torque Ripple Due to Phase Commutation in Brushless dc Machines" IEEE Transactions on Industry applicationsVol. 28, No. 3,

THE KOREAN INSTITUTE OF ELECTRICAL ENGINEERS

'06

대한전기학회 제37회 하계학술대회 논문집

Proceeding of the 37th the KIEE Summer Annual Conference 2006

- 일 시 : 2006년 7월 12일(수) ~ 14일(금)
- 장 소 : 용평리조트(강원도 평창군)

B

- 전기기기
- 전력전자
- 전기교통신기술
- 신재생에너지시스템
- 친환경전기기기
- S-Session(학부생 발표)

www.kiee.or.kr

주 최 : 대한전기학회

후 원 : 한국전력공사 · 한국학술진흥재단
한국과학기술단체총연합회