

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

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

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Abstract - This paper presents a drive strategy to reduce torque ripple of a permanent magnet Brushless DC Motor (BLDCM) with short 120° 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 compensate the 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° 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° 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).

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} + \begin{bmatrix} V_{no0} \\ V_{no0} \\ V_{no0} \end{bmatrix} \quad (1)$$

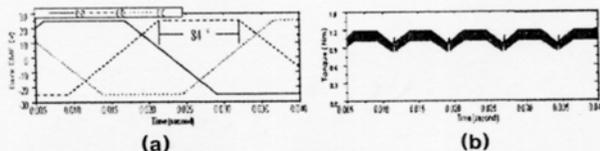
$$T = \frac{1}{\omega} (e_a i_a + e_b i_b + e_c i_c) \quad (2)$$

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).

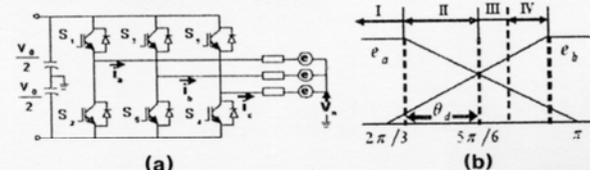
2.1 Section I

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)

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



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



<Fig. 2> (a) the equivalent circuit of a BLDCM drive system (b) the Back-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.

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

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

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

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

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

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

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

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)

$$V_{un0} = -\frac{V_0 S_{32}}{6} - \frac{e_a + e_b + e_c}{3} \quad (9)$$

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

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

2.4 Section IV

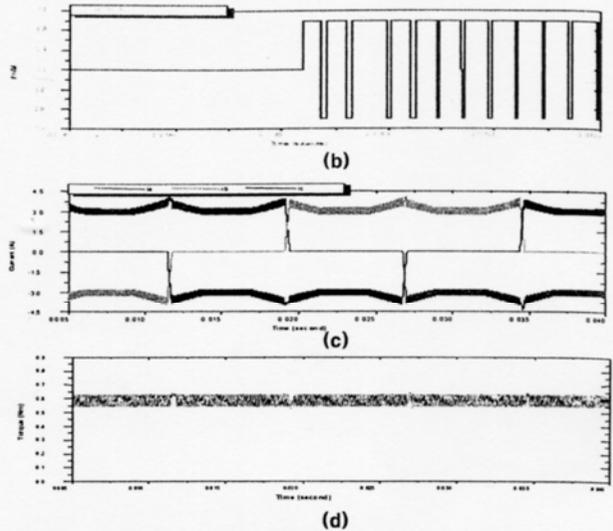
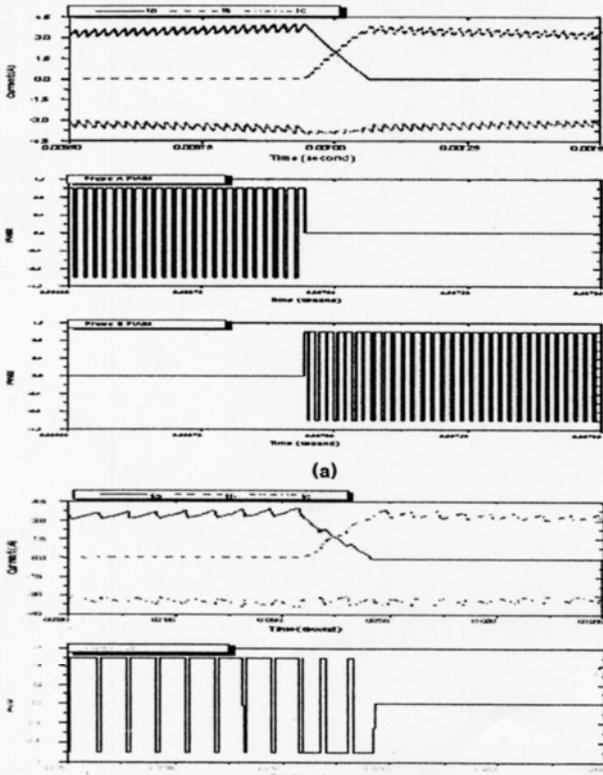
When phase-a current vanishes, the commutation step finishes. But phase-b Back-EMF still is in varying state, which is similar to the phase-a Back-EMF in section II. In the same method with section II, the corresponding PWM duty-ratio is

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

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.



<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 corresponding 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 | $\pi/10$ |
| Phase Inductance | 3.05 (mH) |
| Phase Resistance | 0.75 (Ohm) |
| Speed | 1300 (rpm) |
| Back-EMF | 25 (V) |

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| | | |
|--------|---|-----|
| EMP 47 | 유한요소법을 이용한 전력용 변압기의 2차원 온도분포 예측 이정근, 김종경, 주수원, 한성진 | 751 |
| EMP 48 | 동기형 릴럭턴스 전동기의 토크와 역률의 최대화를 위한 설계 및 해석 김원호, 김기찬, 원성홍, 안준선, 최승길, 이 주 | 753 |
| EMP 49 | 방열기를 갖는 유입자생식 변압기의 온도분포 해석 김종경, 한성진, 오연호, 박경엽 | 755 |
| EMP 50 | 전기자동차를 위한 컨프레샤용 BLDC Motor 구동드라이브에 관한 연구 정경수, 전장건, 최형래, 우 도, 이동현, 이상훈, 박성준, 정태욱 | 757 |
| EMP 51 | BLDC 모터 구동을 위한 신경회로망 PI파라미터 자기 동조 시뮬레이터 배은경, 권중동, 김태우, 김대균, 전지용, 이승환, 이훈구, 김용주, 한경희 | 759 |
| EMP 52 | 신경회로망을 이용한 IPMSM 드라이브의 온라인 파라미터 추정 박기태, 최정식, 고재섭, 이정호, 김종관, 박병상, 정동화 | 761 |
| EMP 53 | 단상 유도형 동기전동기의 파라미터 변화에 따른 동특성 해석 오세영, 정대성, 임승빈, 이 주 | 763 |
| EMP 54 | 극 수와 슬롯 수 조합에 따른 집중권 방식 매입형 영구자석 동기전동기의 Normal Force 및 설계 파라미터의 비교에 관한 연구 하승형, 권순오, 반지형, 정재우, 홍정표 | 765 |
| EMP 55 | BLDC 전동기의 코깅토크 저감을 위한 고정자 설계 유대일, 임승빈, 김기찬, 원성홍, 이 주 | 767 |
| EMP 56 | 실험계획법을 이용한 Magnetic suspension의 최적설계 정재우, 김성일, 하승형, 홍정표, 이주훈 | 769 |
| EMP 57 | 매입형 영구자석 동기전동기의 극 수 슬롯 수 조합에 따른 특성에 관한 연구 반지형, 권순오, 하승형, 홍정표 | 771 |
| EMP 58 | 직접 구동용 5kW AFPM 풍력 발전기 특성 해석 김형길, 김철호, 서영택, 오철수 | 773 |
| EMP 59 | 고효율 영구자석 릴럭턴스 전동기의 설계 및 해석 장 봉, 권순오, 홍정표 | 775 |
| EMP 60 | 반응 표면법을 이용한 Multi-layer 매입형 영구자석 동기전동기의 효율 향상 방 량, 권순오, 이상호, 장 봉, 홍정표 | 777 |
| EMP 61 | 농형 유도전동기의 회전자 바 손상에 따른 특성 해석 김병국, 김미정, 조윤현, 임성환, 황돈하, 강동식 | 779 |
| EMP 62 | 역기전력을 고려 한 브러시리스 전동기의 토크리플 저감에 관한 구동 방식에 대한 연구 손 도, 남기용, 이근호, 홍정표 | 781 |
| EMP 63 | 매입형 영구자석 전동기의 파라미터 검증을 위한 인덕턴스 산정 이석희, 이상호, 반지형, 홍정표 | 783 |
| EMP 64 | 전기자 권선 방법에 따른 매입형 영구자석 동기 전동기의 특성 비교 박수범, 권순오, 김성일, 홍정표 | 785 |
| EMP 65 | 산업용 잉크젯 플로터의 입전세라믹 헤드에 의한 드롭제어 최근수, 윤신용, 백수현, 김 용 | 787 |