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# Advance Angle Calculation for Improvement of the Torque-to-Current Ratio of Brushless DC Motor Drives

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**Abstract**

This paper presents a method of calculating an advance angle in order to increase the torque-to-current ratio of a brushless DC (BLDC) motor. The BLDC motor is widely used in various industrial fields because of its high energy density and low maintenance. Because the BLDC motor drives with a square-wave current of electrical 120 degrees duration, the phase current must be commuted every 60 electrical degrees of rotation. Owing to the inductance levels of the motor winding process, the commutation induces a phase lag and deviations from the ideal square-wave current form. These non-ideal characteristics reduce the torque-to-current ratio. Advancing the commutation timing can improve the torque-to-current ratio. This paper analyzes the torque performances of the BLDC motor and proposes a method of calculating the advance angle in order to improve the torque-to-current ratio. The simulation results of a 20 W, 20,000 rpm BLDC motor verify the effectiveness of the proposed calculation method.



*Keywords*: Brushless DC (BLDC) motor; commutation; torque-to-current ratio; advance angle

## 1. Introduction

The brushless DC (BLDC) motor, which has the advantages of a high energy density and low maintenance, is widely used in various industrial fields, such as medical machines and automotive equipment [1],[2]. Because the BLDC motor drives with a square-wave current of electrical 120 degrees duration, the phase current must be commuted every 60 electrical degrees of rotation. If the winding inductance levels of the motor are minute, the commutation period can be ignored because the current lag is negligible. However, in practice the current characteristics of a BLDC motor seldom match the ideal characteristics. Owing to the inductance levels of the motor winding process, the commutation induces a phase lag and deviations from the ideal square-wave current form [3]. These non-ideal characteristics reduce the torque-to-current ratio. Adjusting the commutation timing prior to the nominal timing can improve the torque-to-current ratio [4],[5].

We analyze the torque performances of the BLDC motor and propose a method of calculating the advance angle in order to improve the torque-to-current ratio.

**Nomenclature**

| | |
|---|---|
| $e$ | phase back electromotive force (EMF) |
| $E_m$ | magnitude of the back EMF |

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| | |
|---|---|
| $i$ | phase current |
| $I_m$ | magnitude of current |
| $V_{dc}$ | DC-link voltage |
| $\tau_e$ | electronic torque |
| $p$ | instantaneous power |
| $P$ | average power |
| $\omega_m$ | mechanical angular velocity |
| $\theta_{comm}$ | commutation interval |
| $\theta_{adv}$ | advance angle |

## 2. Calculation method of the advance angle

### 2.1. Back EMF and current waveform analysis

To obtain the constant torque of a BLDC motor that drives with a square-wave current of electrical 120 degrees duration, we need to ensure, as shown in Fig. 1(a), that the phase current is commuted every 60 electrical degrees of rotation. The electronic torque is expressed as follows:

$$\tau_e = \frac{p}{\omega_m} = \frac{p_a + p_b + p_c}{\omega_m} = \frac{e_a \cdot i_a + e_b \cdot i_b + e_c \cdot i_c}{\omega_m} \tag{1}$$

As shown in Fig. 1(b), a commutation induces a phase lag and deviations from the ideal square-wave current as a result of the inductance levels of the motor winding process. The dotted line in Fig. 1(b) indicates the phase current of the advanced commutation timing. The torque characteristic is changed by the commutation timing because torque, as indicated in (1), is derived from the multiplication of the back EMF and the phase current. The advance angle, which maximizes the torque-to-current ratio, can be calculated by analyzing the average power variation in relation to the advance angle.

The average power of phase A is given as follows:

$$P_a = \frac{1}{\pi}\int_0^{\pi} e_a \cdot i_a d\theta \tag{2}$$

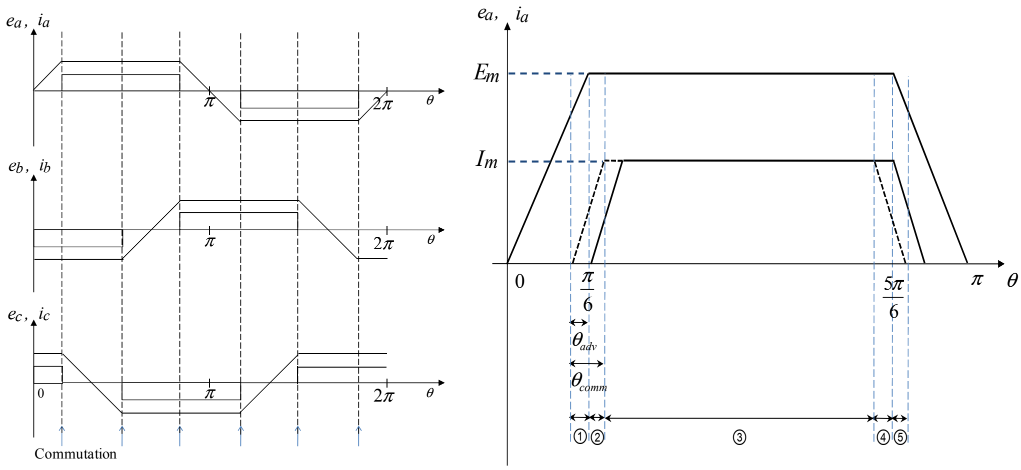

Fig. 1. (a) The back EMF and current waveform of a BLDC motor; (b) the back EMF and current waveform of one phase

In Fig. 1(b), an integral cross section of the average power is divided from ① to ⑤ in relation to the back EMF and the phase current waveform. The parameters $E_m$ and $I_m$ denote the maximum value of the back EMF and the phase current. The parameters $e$ and $i$ are calculated as follows:

- The back EMF equation from zero to $\pi$ :

$$e = \begin{cases} \dfrac{E_m}{\pi/6} \;, & 0 \le \theta \le \dfrac{\pi}{6} \\ E_m \;, & \dfrac{\pi}{6} \le \theta \le \dfrac{5\pi}{6} \\ E_m - \dfrac{E_m}{\pi/6}\left(\theta - \dfrac{5\pi}{6}\right) \;, & \dfrac{5\pi}{6} \le \theta \le \pi \end{cases} \tag{3}$$

- The phase current equation in the range of zero to $\pi$ :

$$i = \begin{cases} \dfrac{I_m}{\theta_{comm}}\left(\theta - \dfrac{\pi}{6} + \theta_{adv}\right) \;, & \dfrac{\pi}{6} - \theta_{adv} \le \theta \le \dfrac{\pi}{6} + \theta_{comm} - \theta_{adv} \\ I_m \;, & \dfrac{\pi}{6} + \theta_{comm} - \theta_{adv} \le \theta \le \dfrac{5\pi}{6} - \theta_{adv} \\ I_m - \dfrac{I_m}{\theta_{comm}}\left(\theta - \dfrac{5\pi}{6} + \theta_{adv}\right) \;, & \dfrac{5\pi}{6} - \theta_{adv} \le \theta \le \dfrac{5\pi}{6} + \theta_{comm} - \theta_{adv} \end{cases} \tag{4}$$

*2.2. Calculation of the advance angle*

The average power for each cross section is calculated in (3) and (4). The equation for the advance angle can be expressed as follows:

$$P = \frac{2 \cdot E_m \cdot I_m}{3\pi} - \frac{E_m \cdot I_m \cdot \theta_{comm}^2}{\pi^2} + \frac{3 \cdot E_m \cdot I_m \cdot \theta_{comm}}{\pi^2} \cdot \theta_{adv} - \frac{3 \cdot E_m \cdot I_m}{\pi^2} \cdot \theta_{adv}^2 \tag{5}$$

The average power, which is a quadratic function of the advance angle, has a maximum value because the coefficient of the quadratic term is negative. The maximum average power is derived as follows:

$$\frac{dP}{d\theta_{adv}} = \frac{3 \cdot E_m \cdot I_m}{\pi^2}\left(\theta_{comm} - 2 \cdot \theta_{adv}\right) = 0 \tag{6}$$

Thus, the advance angle can be calculated as follows:

$$\theta_{adv} = \frac{\theta_{comm}}{2} \tag{7}$$

As shown in (7), the advance angle for the maximal torque-to-current ratio is half the commutation interval. The commutation interval ($\theta_{comm}$) is calculated as follows [6]:

$$\theta_{comm} = \frac{\omega_m \cdot L \cdot I_m}{V_{dc}} \tag{8}$$

The result of the calculation of the advance angle changes in relation to the actual phase current and the back EMF, which are determined in (3) and (4). However, the calculation method and process are the same as (5), (6), and (7).

## 3. Simulation results

We used a model of a BLDC motor to consider the behavior of the commutation and the waveform of the back EMF in a dynamic simulation under the MATLAB/Simulink environment [7],[8],[9]. Table 1 shows the motor parameters used to examine the performance of the advance angle.

Table 1. Parameters of the BLDC motor

| Parameters | Value | Unit |
|---|---|---|
| DC bus voltage | 24 | $[V]$ |
| Phase resistance | 0.33 | $[\Omega]$ |
| Phase inductance | 0.04 | $[mH]$ |
| Back EMF constant | 6.75 | $[V_{rms} / rad / s]$ |
| Rated power | 20 | $[W]$ |
| Rated speed | 20000 | $[rpm]$ |

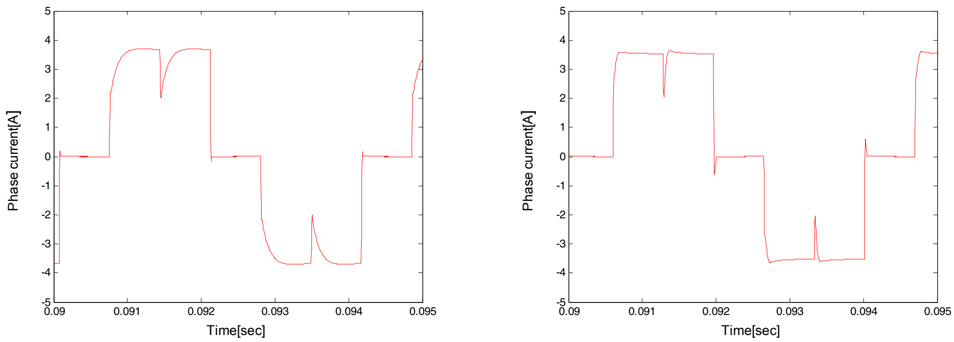


Fig. 2. (a) A phase current waveform without an advance angle; (b) a phase current waveform with an advance angle

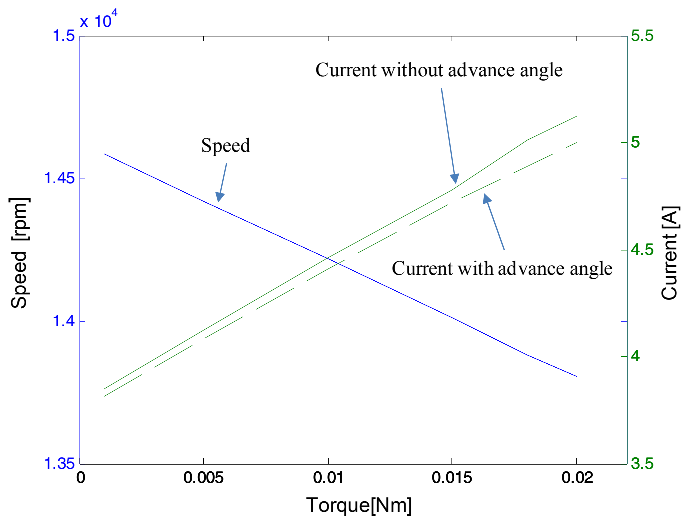


Fig. 3. N-T curve and current

The phase current waveforms for a torque of 0.02 Nm are shown in Figs. 2(a) and 2(b). Fig 2(a) shows what happens when the advance angle is applied; Fig. 2(b) shows what happens when there is no advance angle. Fig. 2(b) resembles the ideal square wave more closely than Fig. 2(a).

Fig. 3 shows the characteristic curves of the motor speed, torque, and current. The solid line represents the current without the advance angle, and the dotted line represents the current with the advance angle.

After the current values are averaged, the average torque-to-current ratio shows an improvement from 1.3%, and the maximum torque-to-current ratio shows an improvement of 2.3%.

## 4. Conclusion

In this paper we analyze the torque performance of a BLDC motor and propose a method of calculating the advance angle in order to improve the torque-to-current ratio.

We analyzed the torque-to-current ratio in relation to the characteristic curves of the motor speed, torque, and current. The maximum value of the torque-to-current ratio is determined by the advance angle which yields the maximum average power.

We applied the proposed calculation method to a 20 W, 20,000 rpm BLDC motor. The simulation results show an average improvement of 1.3% in the torque-to-current ratio of the sample motor. The results suggest that the system efficiency may be improved because the BLDC drive system produces more torque with less current.


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