Commutation point correction method of sensorless BLDC motor based on back emf detection

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Abstract. For sensorless brushless DC (BLDC) motors, whose rotor position is calculated by the applied estimation techniques, the estimation accuracy is hence a critical factor for the motors’ operating performance. In this paper, respective effects of the estimated rotor position error on the phase current and terminal voltage are analyzed theoretically. Accordingly, a novel commutation point correction method is proposed, which allows the automatic symmetrical modulation of the terminal voltage. In particularly, the commutation point is adjusted on-line by means of closed-loop control of the delayed angle. The proposed technique presents several valuable advantages: 1) it requires no additional hardware implementation; 2) guarantees accuracy and stability of method in the high speed range. The above-mentioned features are verified experimentally on a 4-pole sensorless BLDC motor.

1. Introduction

In recent years, rare-earth permanent magnet brushless direct current (BLDC) motors are widely used in industry, computers, aeronautics and astronautics due to its high power density and high efficiency [1, 2]. The rotor position sensor is an important part of the BLDC motor, but it also brings problems. The implementation of position sensors reduces the reliability of the motor, increases the cost and volume of motor. Additionally, it shows relatively low reliability under critical working conditions (e.g., high temperature, serious mechanical vibrations). Consequently, extensive research interests are triggered in the field of sensorless BLDC motors.

Various techniques can be found in literatures to realize the detection of the rotor position. These methods are based on the back electromotive force (EMF), magnetic flux observation or phase inductance, among which, back EMF based method is superior thanks to its simplicity and reliability. In general, the back EMF based method can be split into two types: terminal voltage method and line voltage method. Apart from these, different estimation approaches can also be applied to extract the back EMF information, for instance, Kalman observer [3], sliding mode observer [4], and other parameter estimation methods [5, 6].

For the back EMF based methods, low-pass filter, computation delay, armature reaction accumulate the detection error, which will attenuate the estimation precise as well as the operation performance of the sensorless BLDC motors. As discussed in [7], the motor phase current can be distorted by any mismatch of the proper commutation points. The larger the estimation error, the more serious the distortion, which may lead to the collapse of the normal operation.

The influence of the armature reaction on the rotor position detection of the salient pole motor was analyzed in [8]. The relationship between the non-conducting freewheeling current and the motor commutation signal was also analyzed in [9]. The main conclusion is that the non-conducting...
The freewheeling current waveform could reflect commutation position error of the BLDCM. The relationship between the phase error of the terminal voltage waveform and the commutation signal in the H_PWM-L_PWM modulation mode is analyzed to verify the accuracy of the commutations. The position of the rotor is corrected by PI closed-loop control [10]. While, the relationship between the waveform of the three-phase current and the position error of the commutation point was analyzed in [11]. The researcher in [12] presents a novel adaptive commutation error compensation method for the BLDC motor based on the flux linkage function. In [13], an improved closed-loop control strategy based on change of current is proposed. This type of error will inevitably result in many adverse effects, such as inaccurate motor commutation, therefore affecting the operation performance of the BLDC motor, leading to vibrations or even failure of synchronization.

2. Mathematical model of BLDC motor

The drive circuit of the BLDC motor is shown in figure 1. The N point is the neutral point of the three-phase BLDC motor. The three-phase six-state control strategy and HPWM_LON modulation method are used to drive the BLDC motor.

![Figure 1. Drive circuit of the BLDC motor.](image)

The following assumptions are made for the mathematical model of the BLDC motor. The three-phase stator windings of the motor are the same. The eddy current, skin effect and hysteresis loss are ignored. From figure 1, the voltage equation of a BLDC motor can be described as follows:

\[
\begin{bmatrix}
U_a \\
U_b \\
U_c \\
\end{bmatrix} =
\begin{bmatrix}
R & 0 & 0 \\
0 & R & 0 \\
0 & 0 & R \\
\end{bmatrix}
\begin{bmatrix}
\dot{i}_a \\
\dot{i}_b \\
\dot{i}_c \\
\end{bmatrix} +
\begin{bmatrix}
L & 0 & 0 \\
0 & L & 0 \\
0 & 0 & L \\
\end{bmatrix}
\begin{bmatrix}
\dot{i}_a \\
\dot{i}_b \\
\dot{i}_c \\
\end{bmatrix} +
\begin{bmatrix}
e_a \\
e_b \\
e_c \\
\end{bmatrix} +
\begin{bmatrix}
u_N \\
\end{bmatrix}
\]

(1)

Where, \(U_a, U_b, U_c\) are the phase to ground voltages (terminal voltage), \(i_a, i_b, i_c\) are the phase currents, \(L\) is the phase inductance, \(R\) is the phase resistance, \(u_N\) is the voltage of neutral point. Figure 2 shows trapezoidal back EMF waveforms.

3. Commutation analysis of BLDC motor

The phase B winding of the motor is conduction and the phase A and phase C windings are in commutation, when the motor runs in the range from 120° to 240° shown in figure 3. When the motor runs in the range from 60° to 120° and 240° to 300° shown in figure 3, the phase B winding is non-conducting. Because of the inductance in the motor winding and the HPWM_LON modulation, each phase will generate a freewheeling current without conducting. In the following, the freewheeling current and terminal voltage during non-conduction under the condition of accuracy, lead and lag commutation is analyzed.
3.1. Accuracy commutation phase B current waveform

Take the motor running in the range from 60° to 120° in figure 3 as an example. PWM control is applied to VT1, and VT2 is on state. When the PWM is turned on, as shown in figure 4, VT1 and VT2 are on state.

The phase B winding generates a freewheeling current. Since the winding has inductance, the current gradually decreases. From (1), a equation can be defined as

$$ L \frac{di_b}{dt} + R_i = \frac{-U_a + 2U_{VD} - 2e_b}{3} $$

Where, $U_{VT}$ is triode forward conduction voltage. $U_a = U_{a} - U_{VT}$, $U_b = U_{VD}$, $U_c = U_{VT}$, $e_a = -e_c = E$, $e_b < E$, $E < U_a/2$, $i_a + i_b + i_c = 0$. Solve the equation of freewheeling current as

$$ i_{b1} = \frac{-U_a + 2U_{VD} - 2e_b}{3R} + C_i \exp(-\frac{t}{\tau}) $$

Where, $C_i$ is determined by the phase B current at the initial moment of each PWM cycle.

When the PWM is turned off, as shown in figure 4, VT1 is off state and VT2 is on state. The phase B winding generates a freewheeling current. Since the winding has inductance, the current gradually increases. $U_a = U_b = U_{VD}$, $U_c = U_{VT}$, $e_a = -e_c = E$, $e_b < E$, $E < U_a/2$, $i_a + i_b + i_c = 0$. From (1), a equation can be defined as

$$ L \frac{di_b}{dt} + R_i = \frac{U_{VT} - 2e_b}{3} $$

Where, $U_{VD}$ is diode forward conduction voltage. Solve the equation of freewheeling current as

$$ i_{b2} = \frac{U_{VT} - 2e_b}{3R} + C_i \exp(-\frac{t}{\tau}) $$

Where, $C_i$ is determined by the phase B current at the initial moment of each PWM cycle.
As shown in figure 5 in the range from 60° to 90°, when the PWM is turned off, the freewheeling current is continuously increased; Opposite of this, when the PWM is turned on, the freewheeling current is continuously decreased. The phase B current decreases with the increase of phase B back EMF at each chopping cycle until the steady-state component of the freewheeling current is zero.

Figure 5. PWM(OFF).

Similarly, when the motor is operating in the range from 240° to 300° in figure 5, the B phase is still non-conducting. When the PWM is turned on and off, the B phase currents are \(i_{b1}\) and \(i_{b2}\) which are same as equation (3) and (5). The freewheeling current change process is also the same as in the range of 60° to 120°. In each commutation cycle, the average values of current within the range of 60° to 120° and the range from 240° to 300° are expressed as \(I_{f1}\) and \(I_{f2}\). The difference value between them is \(\Delta I = I_{f1} - I_{f2}\). Therefore, when the motor is accuracy commutation, the current waveform is symmetrical in a commutation cycle. The mean value of the freewheeling currents in both sections is equal, which is \(\Delta I = 0\).

The average of current within the range of 60° to 120° and the range from 240° to 300° in each commutation cycle called \(U_1\) and \(U_2\), shown in figure 3. Calculate the phase B voltage difference, which is \(\Delta U_b = U_{b1} - U_{b2}\). The terminal voltage is an asymmetry trapezoidal waveform when the motor is accuracy commutation. The \(\Delta U_b\) should be equal to zero (\(\Delta U_b = 0\)) within accuracy commutation.

3.2. Lead commutation phase B current waveform

When the motor is lead commutation, phase B is the non-conduction phase, as shown in figure 6. Assuming that the lead angle is \(\alpha\), the phase B freewheeling current in the range from 60° - \(\alpha\) to 120° - \(\alpha\) is analyzed. When the motor is running in the range from 60° - \(\alpha\) to 60°, the VT1 is PWM(ON). \(U_a = U_{a1}, U_c = U_{b} = 0, e_a = -e_b = E, e_i < E, E < U_d / 2, i_a + i_b + i_c = 0\). From (1), a equation can be defined as

\[
L \frac{di_b}{dt} + R_i = \frac{3E + e_e - U_d + 2U_{vd}}{3} \tag{6}
\]

Solve the equation of freewheeling current as

\[
i_{b11} = \frac{3E + e_e - U_d + 2U_{vd}}{3R} + C_1 \exp(-\frac{t}{\tau}) \tag{7}
\]

When the motor is running in the range From 60° - \(\alpha\) to 60°, the VT1 is PWM(OFF). \(U_a = U_{b1} = U_{vd}, U_c = U_{vt}, e_a = -e_b = E, e_i < E, E < U_d / 2, i_a + i_b + i_c = 0\). From (1), a equation can be defined as

\[
L \frac{di_b}{dt} + R_i = \frac{3E + e_e + U_{vd} - U_{vt}}{3} \tag{8}
\]

Solve the equation of freewheeling current as

\[
i_{b21} = \frac{3E + e_e + U_{vd} - U_{vt}}{3R} + C_2 \exp(-\frac{t}{\tau}) \tag{9}
\]
As shown in figure 6 in the range from 60° − α to 60° , when the PWM is turned off, the freewheeling current is continuously increased; Opposite of this, when the PWM is turned on, the freewheeling current is continuously decreased. The phase B current decreases with the increase of phase C back EMF at each chopping cycle. When the motor is running in the range from 60° to 120° − α , the equations of the freewheeling current in PWM(ON) and PWM(OFF) are equation (3) and (5), respectively, which are the same as the accuracy commutation.

\[
i_{b_{21}} = \frac{-3E + e_c - U_v + 2U_{VD} + C_1 \exp\left(-\frac{t}{\tau}\right)}{3R}
\]

\[
i_{b_{21}} = \frac{-3E + e_c + U_v - U_{VT} + C_2 \exp\left(-\frac{t}{\tau}\right)}{3R}
\]

Therefore, when lead commutation occurs, the current waveform is asymmetric in a commutation cycle. In each commutation cycle, the average values of freewheeling current within the range from 60° − α to 120° − α and the range from 240° − α to 300° − α are also expressed as \(I_{f_1}\) and \(I_{f_2}\). The average values of the current in both sections are not equal, and difference value between them is greater than zero (\(\Delta I > 0\)). The greater the angle \(\alpha\) is, the greater the \(\Delta I\) is.

3.3. Lag commutation phase B current waveform

Therefore, when lag commutation occurs, the current waveform is asymmetric in a commutation cycle, which is the opposite of the current wave in the lead commutation shown in figure 7. In each commutation cycle, the average values of current within the range from 60° + α to 120° + α and the range from 240° + α to 300° + α are expressed as \(I_{f_1}\) and \(I_{f_2}\). The average value of the currents in both sections is not equal, and difference value between then is smaller than zero (\(\Delta I < 0\)). The smaller the angle \(\alpha\) is, the smaller the \(\Delta I\) is.
Figure 7. Lag commutation phase B current and terminal voltage.

The terminal voltage is not a asymmetry trapezoidal waveform when the motor is lead and lag commutation. The $\Delta U_b$ should be less than zero ($\Delta U_b < 0$) within lead commutation. To the opposite, the $\Delta U_b$ should be more than zero ($\Delta U_b > 0$) within lag commutation.

4. A novel method of commutation correction

During the operation of BLDCM, ideally, the back EMF is trapezoidal and the phase current is a rectangular wave. When commutation is accurate, the motor output torque is maximum and the operation is most stable. Owing to the three-phase six-state control strategy of the BLDC motor, the commutation points are obtained from the zero-crossing points of back EMF. However, due to back EMF sensorless control strategy often causes lead or lag commutation, the motor runs unsteadily and causes greater torque pulsation.

Through the above analysis of the phase current and terminal voltage waveforms of the BLDC motor, they will generate waveform distortion when commutation is inaccurate, which is used as a criterion to correct the commutation point.

Due to the back EMF method is used widely in sensorless BLDC motor, it is necessary to detect the terminal voltage at all times. Therefore, the commutation point correction method is to control the terminal voltage waveform to maintain symmetry without adding new devices. This method is relatively simple and reliable without additional devices such as three-phase current sensors. The flow chart is shown in figure 8. From this, the block diagram of motor system and control algorithm is shown in figure 9.

The specific steps of this method are as follows:

Step 1: Counting the time three quarters duty cycle in each chopping cycle (three quarters duty cycle, the sampled motor voltage is more accurate [14]). At this time, reading and calculating the data of ADC, the actual value of the three-phase terminal voltage ($U_a, U_b, U_c$) of the motor is obtained.

Step 2: Record the phase B terminal voltage value $U_b$ in the range 60 degrees before and after the phase B conduction. It is also the terminal voltage value in the range of $60^\circ \pm \alpha$ to $120^\circ \pm \alpha$ and $240^\circ \pm \alpha$ to $300^\circ \pm \alpha$ in figure 3, 6, 7. (When commutation is accurate, $\alpha$ is equal to zero; When commutation is inaccurate, $\alpha$ is not equal to zero.)

Step 3: A set of voltage value $U_b$ are digitally filtered in the range of $60^\circ \pm \alpha$ to $120^\circ \pm \alpha$. After removing the maximum and minimum values, the remaining values are averaged $U_{b1}$. In the range from $240^\circ \pm \alpha$ to $300^\circ \pm \alpha$, as the same method, $U_{b2}$ is obtained. Calculate the phase B voltage difference, which is $\Delta U_b = U_{b1} - U_{b2}$.
Obtain $U_b$ and $U_{b2}$

Filter and calculation

$\Delta U_b > 0$ or $\Delta U_b < 0$

$\Delta U_b = U_{b2} - U_{b1}$

$\Delta U_b > 0$

$\Delta U_b < 0$

$\Delta U_b = 0$

Sample terminal voltage

Commutation

Start

End

Figure 8. Algorithm flow chart.

Step 4: The phase B terminal voltage difference can reflect the phase position error of the commutation signal of the BLDC motor. When $\Delta U_b = 0$, the commutation is accurate; When $\Delta U_b < 0$, the commutation is lead, using PI regulation to reduce the delayed angle of the zero-crossing point to commutation point; When $\Delta U_b > 0$, the commutation is lag, using PI regulation to increase the delayed...
angle of the zero-crossing point to the commutation point. In turn, accuracy commutation adjustment with zero phase error can be achieved.

5. Experimental verification
With the development of digital chip technology, the BLDC motor control system has evolved from traditional analog circuit control to digital-analog hybrid circuits with MCU. The digital controller based on a DSP (TMS320F28335) has been implemented. The inverter is established by PM300CSD060 module. The data of three-phase terminal voltage collection and calculation are needed to acquire zero-cross point of back EMF and estimate the rotor position. The commutation is performed after a certain delayed electrical angle to realize accuracy commutation of the motor and drive the motor.

![Figure 10. Motor controller.](image)

![Figure 11. Motor experimental system.](image)

Figure 10 shows motor controller. Figure 11 illustrates the configuration of motor control system for experiments. The validity of the proposed commutation point correction method is verified by sensorless BLDCM. The parameters of the motor control system are listed in table 1.

| Table 1. Motor control system parameters. |
|------------------------------------------|
| Motor controller DC power supply          | 28V |
| Motor DC power supply                    | 270V |
| Rated speed                              | 8000r/min |
| Rated power                              | 10kW |
| Pole pairs                               | 2 |
| Phase Resistance                         | 0.253Ω |
| Phase Inductance                         | 0.5457mH |
| PWM modulation frequency                 | 15kHz |

The following results are still taking the phase B as an example. In figure 12, 13, 14, 15, the phase current and the terminal voltage are acquired from an oscilloscope. The time axis of each grid is 1ms. The voltage in each grid of vertical axis is 100V, and the current in each grid of vertical axis is 10A. In the experiment, the motor runs at rated speed.

Figure 12 shows the phase current and terminal voltage waveforms when the motor is running in lead commutation, and the phase current and terminal voltage waveforms after commutation correction are shown in figure 13. Figure 14 shows the phase current and the terminal voltage waveforms when the motor is running in lag commutation, and the phase current and terminal voltage waveforms after commutation correction are shown in figure 15. By comparing the waveforms, it is verified that the commutation point correction method is effective and feasible.
6. Conclusions
A commutation-point estimation method is proposed in this paper for sensorless BLDC motors. It allows on-line auto-correcting of the commutation points by means of closed-loop control of the detected phase error. The proposed technique is based on the relationship between phase error and symmetricity of the terminal voltage. The proposed technique requires no additional hardware implementation, thanks to its simplicity and reliability. The valuable features, mentioned above, making it a promising choice for cost-sensitive industrial applications.

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