Torque ripple reduction of BLDC motor based on DC bus voltage automatic selection circuit and neutral point clamped three-level inverter control

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Abstract. The torque ripple of Brushless direct current motor (BLDCM) mainly depends on the commutation torque ripple, while the commutation torque ripple mainly depends on the current fluctuation during commutation. In this paper, the cause of current fluctuation during commutation is analyzed, and an automatic selection circuit based on DC bus voltage and a neutral-point-clamped (NPC) three-level inverter controller is proposed. The motor winding is guaranteed to bear half of the DC bus voltage, and the duty cycle is calculated so that the DC bus voltage at the moment of phase change is in a certain relationship with the back electromotive force (EMF) of the circuit, thus suppressing the current ripple during phase change and achieving the purpose of suppressing torque ripple during phase change.

Keywords: Brushless DC motor (BLDCM), commutation torque ripple, DC bus voltage, neutral-point-clamped (NPC) three-level inverter.

1. Introduction
Brushless DC motor (BLDCM) has many advantages such as small volume, simple construction, good power density, simple maintenance and wide speed range etc. BLDCM with trapezoidal wave back electromotive force (EMF) are extensively used in intelligent home, industrial automation, robot and intelligent manufacturing, automobile, medical care and automatic motion control of defense and military industry [1]-[2]. The traditional conducting control strategy inevitably produces torque ripple, which mainly produces vibration, speed ripple and noise, so the reduction of torque ripple is extremely important for the secure and stable performance of BLDCM [3]-[4].

Based on torque estimation and inverter voltage space vector, a novel BLDCM Direct Torque Control (DTC) was proposed to control the instantaneous torque and reduce the torque ripple [5]. The Field-Oriented Control (FOC) scheme for BLDCM driven by voltage source inverter (VSI) is realized by using sinusoidal and space vector pulse width modulation to control the motor parameters on d-q axis [6]. The proposed phase change compensation technology is based on a strategy to control the input phase and output phase current slope in the phase change interval by adjusting the appropriate duty ratio equalization. A single DC sensor and current differential beat control are used to effectively suppress phase change torque ripple in the low and high speed operating regions of the BLDCM [7].
Adding a buck converter in front of the single-current-sensor BLDCM inverter can reduce the torque ripple both in the conduction region and in the phase change region [8]. A new structure of low cost BLDCM drive system based on current sensor and proportion integral derivative (PID) controller is proposed. Compared with the traditional drive system, the torque ripple is smaller [9].

The duty cycle of pulse width modulation is calculated by measuring the phase change interval at the terminal voltage of BLDCM, and the compensation strategy of voltage disturbance is obtained to suppress the next phase change torque ripple, a new method for reducing phase change torque ripple of sensorless BLDCM driver without current sensor is presented [10]. In short, the factors that cause the torque ripple are very complex, and different control methods should be adopted for different situations. Each method has its own advantages and disadvantages as well as its own adaptive situation. In different environments, different methods can be adopted for different requirements.

For the six-step phase change technique of three-phase BLDCM, under the two-two conduction mode enables the two switches to be switched on at the same time, and the phase change changes the switch state once every 60°, only one switch tube is changed at a time, each switch tube is continuously turned on at 120°, the current change on the phase change winding can not be completed in a moment, but there is a changing process, therefore, the current wave will be produced when the phase change is carried out, which causes the phase change torque ripple. In this paper, the cause of phase change torque ripple under 120°conduction mode are studied, and a strategy of suppressing phase change torque ripple based on DC busbar voltage automatic selection circuit is proposed [11]-[13].

2. Analysis of Torque Ripple in BLDCM System

2.1. Mathematical model of BLDCM

The stator windings of trapezoidal back EMF BLDCM are generally connected by symmetrical three-phase Y-type method. Each phase has the same resistance and inductance values \( R_a = R_b = R_c = R \), \( L_a = L_b = L_c = L \). The winding of each phase can be equated to the series formation of resistance, inductance and back EMF. The equivalent model of BLDCM controlled by two-level inverter is shown in Fig. 1. The diagram of phase current, back EMF and conduction device is shown in Fig. 2.

![Figure 1. Equivalent model of BLDCM two-level inverter](image)

![Figure 2. The relation between phase current, opposite EMF and conduction device of BLDCM](image)
The mathematical model of BLDCM is expressed in the following:

\[
\begin{bmatrix}
U_a \\
U_b \\
U_c \\
\end{bmatrix} =
\begin{bmatrix}
R & 0 & 0 \\
0 & R & 0 \\
0 & 0 & R \\
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c \\
\end{bmatrix} +
\begin{bmatrix}
L & 0 & 0 \\
0 & L & 0 \\
0 & 0 & L \\
\end{bmatrix}
\frac{d}{dt}
\begin{bmatrix}
i_a \\
i_b \\
i_c \\
\end{bmatrix} +
\begin{bmatrix}
e_a \\
e_b \\
e_c \\
\end{bmatrix} +
\begin{bmatrix}
U_n \\
U_n \\
U_n \\
\end{bmatrix}
\]

(1)

Where \(U_a, U_b, U_c\) are phase voltages of three-phase stator windings, \(R\) is resistance of three-phase windings, \(L\) is self-inductance of three-phase windings, \(i_a, i_b, i_c\) are phase currents of three-phase stator windings, \(e_a, e_b, e_c\) are three-phase back EMF, \(U_n\) is the neutral point to ground voltage. According to the symmetry of the stator three-phase windings with Y-type connection and no centerline, the relationship between the three-phase current is as follows[1]:

\[i_a + i_b + i_c = 0\]

(2)

The output electromagnetic power of the motor is:

\[P_e = e_a i_a + e_b i_b + e_c i_c\]

(3)

The electromagnetic torque generated by a BLDCM is expressed as:

\[T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m}\]

(4)

Where \(\omega_m\) is the mechanical angular velocity of the rotor.

The electromagnetic torque of the BLDCM is similar to that of the ordinary DC motor, and its electromagnetic torque is proportional to the magnitude of the back EMF and the amplitude of the current, so the torque of BLDCM can be controlled by changing the amplitude of output current of inverter as square wave. In order to produce a continuous electromagnetic torque, the stator current is required to be a standard square wave, the back EMF is required to be a standard trapezoid wave, and the duration of the square wave current is 120° electric angle in every half period, the fixed top partion of the trapezoidal wave back EMF is also 120° electric angle, the two should be in strict synchronization.

The BLDCM rotor motion equation is:

\[J \frac{d\Omega}{dt} = T_e - T_L - T_0\]

(5)

Where \(J\) is the the rotor and the load inertia, \(T_L\) is the load torque and \(T_0\) is the no-load torque. The above equations combine to form a complete mathematical model of BLDCM system.

2.2. Definition of commutation torque ripple of BLDCM:

It is of great significance to give a proper definition of torque ripple to measure the torque ripple and to put forward an effective strategy to inhibit the torque ripple.

The change in speed caused by torque ripple is regarded as more significant than the torque ripple itself, and therefore the torque ripple is defined as [14]:

\[\nabla \Omega = \frac{1}{J} \int_{t_1}^{t_2} (T_e - T_{eo}) dt\]

(6)

In the equation, \(\Omega\) is the mechanical angular velocity of the motor, \(J\) is the rotational inertia, \(T_e\) is the instantaneous value of electromagnetic torque, \(T_{eo}\) is the steady state electromagnetic torque.

The torque ripple can be defined as [15]:

\[\nabla T_e = \frac{T_{e\text{ max}} - T_{e\text{ min}}}{T_{e\text{ av}}} \times 100\%\]

(7)

In the equation \(T_{e\text{ max}}\) is the largestvalue of torque, \(T_{e\text{ min}}\) is the minimum torque and \(T_{e\text{ av}}\) is the mean value of torque.

The torque ripple can also be defined as [16]:

\[\nabla T_e = T_e - T_{e\theta}\]

(8)
In the equation $T_e$ is the electromagnetic torque after phase change and $T_{e0}$ is the electromagnetic torque before phase change. In this paper, the definition of phase change torque ripple is given by considering phase change torque ripple.

From the analysis of electromagnetic torque and other calculation equations, it is found that the phase change torque ripple of BLDCM is directly due to the current fluctuation during phase change.

2.3. Torque ripple caused by current ripple during commutation

During the phase change, the motor speed be certain, and the back EMF is an ideal trapezoidal waveform (the width of flat top is 120°). It is considered that the amplitude of each opposite electromotive force is constant during phase change.

As an example, the current is converted from phase C to phase A (upper bridge arm phase change) and phase B is non-commutation. Because the motor winding is inductive, DC voltage is a limited capacity voltage source, so the current change on the commutation winding can not be completed in a moment, but there is a change process. In the two-two-conduction mode, two MOSFETs are switched on at the same time. There are six conduction states, which are changed once every 60°, only one switch tube is changed on each time, and each switch tube is continuously conduction on 120°.

The phase change process is shown in the Fig.3, with MOSFET T5 and T6 conducting before the phase change cycle and phase current flowing through the circuit as shown in Fig.3. (a). T1 conducting at the beginning of the phase change cycle, T5 being disconnected, and then because the current in the inductor can not be changed abruptly, the continuation of the phase C through the flyback diode D2 is shown in Fig.3. (b). The MOSFET T1 and T6 continue on after the phase change, as shown in Fig3. (c). The phase change from phase C to phase A is realized through the above process.

![Figure 3. BLDCM Phase Transition Diagram from phase C to Phase A](image_url)

It is assumed that the time required for the turn-off phase winding to decrease from the maximum current amplitude to zero is $t_f$, and the time required for the turn-on phase winding to increase to the maximum current amplitude is $t_r$. Although all winding parameters of the motor are equal and symmetric, but for different current states, $t_f$ and $t_r$ are not necessarily equal. According to the characteristic that the winding is Y-type connected and the sum of three-phase current is zero, we can get three kinds of current changes as shown in Fig.4.
Fig. 4. shows the current conversion within the phase change period under different speed conditions. The difference of current conversion rate between input phase and output phase results in torque pulsation. In Fig. 4. (a) (b) (c), the off-phase current drop rate is faster than, slower than and equivalent to the on-phase current rise rate. The amplitude of the non-commutating winding current increases when the current changes during phase change as shown in Fig. 4(a), the non-commutating winding current decreases shown in Fig. 4(b), and the non-commutating winding current is constant shown in Fig. 4(c). Assuming that the resistance is negligible and the back EMF is fixed, the phase current change rate during phase change is expressed in the following equation [17]:

\[
\begin{align*}
\frac{di_1}{dt} &= -\frac{U_{dc} + 2E_m}{3L} \\
\frac{di_2}{dt} &= \frac{2(U_{dc} - E_m)}{3L} \\
\frac{di_3}{dt} &= -\frac{V_{dc} - 4E_m}{3L}
\end{align*}
\]  

(9)

Before phase change, electromagnetic torque equation is:

\[T_{e-} = e_i i_1 + e_i i_2 + e_i i_3 = \frac{2I_m E_m}{\omega_m}\]  

(10)

\(E_m\) is the steady-state value of the back EMF.

In time interval \(t_f\), the output phase current changes from steady state value \((I_m)\) to zero, \(t_r\) should be represented as [17]:

\[t_f = \frac{3I_m}{U_{dc} + 2E_m}\]  

(11)

The output phase current from zero to steady-state time \(t_r\) should be expressed as:

\[t_r = \frac{3I_m}{2(U_{dc} - E_m)}\]  

(12)

From Equations (2), (11), and (12), the torque equation for the phase change interval is:

\[T_{e+} = E_m i_1 + E_m i_2 - E_m i_3 + \frac{2E_m i_3}{\omega_m} = \frac{2E_m}{\omega_m} \int \frac{di_3}{dt}\]  

(13)

\[T_{e+} = \frac{2E_m}{\omega_m} (I_m + \frac{U_{dc} - 4E_m}{3L} t)\]  

(14)

The torque ripple is expressed as:
According to the above analysis, $U_{dc}$ is a fixed number, the value of the back EMF $E_m$ is proportional to the motor speed. So $U_{dc} = 4E_m$ is used as the boundary line of BLDCM at low speed and high speed. If $U_{dc} > 4E_m$, motor is in low-speed rotation, motor non-commutation winding current will increase, according to equation (15) then phase change Torque will increase; if $U_{dc} < 4E_m$, motor is in high-speed rotation, motor non-phase change winding current will decrease, the phase change torque ripple is reduced, while it become zero when the DC busbar voltage is adjusted to $4E_m$ under certain speed.

3. Propose the Control Strategy of BLDCM

Based on the analysis of torque ripple, a DC busbar voltage automatic selection circuit is proposed, which, based on the measurement of BLDCM speed, by adjusting the duty cycle of the chopper circuit, the output voltage of the chopper circuit is multiplied with $E_m$, and the DC busbar voltage is switched from the chopper circuit by the automatic selection circuit before phase change. For BLDCM with NPC three-level inverter, the motor windings bear half of the DC busbar voltage, so the DC busbar voltage is close to $8E_m$ based on the speed measurement. In the course of phase change, the DC busbar voltage is applied to reduce the phase change torque ripple.

The topology of the NPC three-level inverter based on the DC busbar voltage automatic selection circuit is shown in Fig.5. In this topology, a NPC three-level inverter is proposed, and a DC busbar voltage automatic selection circuit is introduced to reduce current ripple, so as to reduce the torque ripple. The DC busbar voltage automatic selection circuit consists of MOSFET (T1, T2, T3, T4), which are used to select the required DC busbar voltage to significantly reduce the torque ripple during phase change.

The MOSFET-based NPC three-level inverter operates at 20kHz switching frequency, which provides significant torque ripple reduction compared to the traditional two-level inverter. In a NPC three-level inverter, the DC busbar voltage is turned into three stages by the capacitors $C_1$ and $C_2$. In order to obtain the ideal phase change voltage, the duty cycle of the improved chopper circuit can be adjusted during the non-phase change period to keep the $U_{dc} = 8E_m$. At the beginning of the phase change period, the voltage is supplied from the chopper circuit through the DC busbar voltage automatic selection circuit, which reduces the phase change torque ripple significantly.

$$
\Delta T = T_e - T_e = \frac{U_{dc} - 4E_m}{3L} t
$$

Figure 5. Present a topology of the DC busbar voltage automatic selection circuit and NPC three-level inverter control circuit
The working principle of the NPC three-level inverter circuit is to output positive, zero and negative level. Take phase A as an example, as shown in Fig. 6. When phase A operates at a positive level, the positive current flows from the power supply through MOSFET $T_{A1}$ and $T_{A2}$, and vice versa through diode $D_1$ and $D_2$. When operated at zero level, the positive current flows from the neutral point through clamping diode $D_{A1}$ and over MOSFET $T_{A2}$ and clamping diode $D_{A3}$. When phase A operates at the negative level, the negative current flows from the power supply through the diodes $D_3$ and $D_4$, and vice versa through MOSFET $T_{A3}$ and $T_{A4}$.

The mathematical equation for the output voltage of the chopper circuit is:

$$U_{s2} = \frac{D}{1-D} U_{s1}$$

Where $D$ represents the duty cycle of the chopper circuit, and the back EMF $E$ is proportional to the speed of the motor.

$$E = K_e \times \omega_m$$
The Ke is the back EMF coefficient. Based on the measured motor speed, the duty cycle of the MOSFET can be estimated using the following expression:

$$D = \frac{8K_e\omega_m}{U_s + 8K_e\omega_m}$$

(18)

In practical application, the phase change period of BLDCM is far shorter than that of chopper circuit to adjust the voltage of 8Em at DC side. So the DC busbar voltage automatic selection circuit based on MOSFET is adopted, and the duty cycle of chopper circuit is adjusted by detecting the rotation speed before phase change. Equation (11) is used to estimate the actual phase change period t, which phase change period T is always above t in order to compensate for load or speed changes. Fig.7 shows the flowchart of the claimed control method for the automatic selection of DC busbar voltage.

![Flowchart](image)

Figure 7. The flow chart of the busbar voltage automatic selection circuit is presented

4. Simulation Analysis of Torque Ripple

In MATLAB/Simulink, the simulation model of NPC three-level inverter based on DC busbar voltage automatic selection circuit is set up, and the torque ripple suppression of the proposed scheme is observed [18]-[20].

As shown in Fig.8, the control scheme of the NPC three-level inverter circuit includes an external speed loop and an internal current loop. The speed controller amplifies the error input to the PI controller from the measured speed (ω_m) and the speed reference (ω_m^*) through the comparator. The reference current signal calculated by the speed PI controller is compared with the current signal measured by the BLDCM. The synthesized control voltage signal is generated and compared with the positive trigonometric and negative trigonometric waves. The PWM signal which is fed back together with Hall signals given to the NPC three-level inverter circuit, the speed of BLDCM is constant.
Matlab modeling and simulation are carried out based on the proposed topology. Fig 9 shows the simulated waveforms of BLDCM torque under different working environments. The simulation waveforms show that the proposed topology and method can significantly reduce the phase change torque ripple.

![Figure 8](image.png)

**Figure 8.** The PWM controller block diagram of the proposed NPC three-level inverter circuit

![Figure 9](image.png)

**Figure 9.** BLDCM torque waveforms of the two-level inverter-fed and the proposed topology-fed are simulated. (a) At 300 revolutions per minute (RPM) and 5N·m with 10 kHz switching frequency. (b) At 300RPM and 10N·m with 10 kHz switching frequency. (c) At 300RPM and 5N·m with 20 kHz switching frequency. (d) At 300RPM and 10N·m with 20 kHz switching frequency.

5. Conclusion

In this paper, an automatic selection circuit based on DC busbar voltage and a NPC three-level inverter topology are proposed to reduce phase change torque ripple of BLDCM. According to the proposed circuit simulation model for simulation testing, by comparing with two-level inverter, the test results show that the proposed DC busbar voltage automatic selection circuit can effectively reduce the torque ripple caused by phase change. In order to reduce the output voltage harmonic, reduce the current ripple and improve the robustness of the motor, Sepic chopper circuit, DC busbar voltage automatic selection circuit and NPC three-level inverter are adopted, together, the three components can reduce the phase change torque ripple while making the BLDCM run smoothly and efficiently.
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