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Research on torque ripple suppression of BLDCM method based on Cuk converter

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Abstract. Due to the different manufacturing process and control mode, the commutation torque ripple will occur in the operation of BLDCM(Brushless DC motor). In this paper, the problem of BLDCM torque ripple is analyzed theoretically. In order to suppress the torque ripple during commutation, a method of combining Cuk converter with power inverter circuit is proposed. By changing the bus voltage, the DC bus voltage can be reduced at low speed and increased at high speed, so that the torque ripple of BLDCM can be suppressed at full speed. The simulation results are verified by MATLAB/Simulink, and the simulation results show the effectiveness of the method.

Key words: BLDCM;Cuk converter;Commutation torque ripple suppression;MATLAB simulation

1. Introduction

BLDCM is widely used in many applications due to its high energy density, simple control method, large output torque and stable operation[1].While the motor inevitably generates torque ripple during manufacturing and control, which limits the application of BLDCM in high standard servo field[2,3]. Therefore, suppressing or eliminating torque ripple becomes a problem that must be solved.

In this paper, the combination of Cuk converter and power inverter circuit is used to change the DC bus voltage. By changing the bus voltage,the torque ripple suppression of BLDCM at full speed section is realized.

2. Analysis of working principle of BLDCM

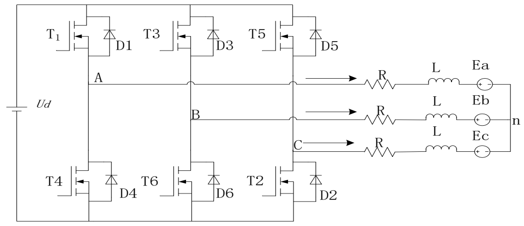

Figure 1. BLDCM circuit structure and driver circuit

Figure 1 shows a three-phase Y-connected brushless DC motor and its drive circuit[4].The stator voltage equation, state equation and torque equation are as follows:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + p \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{1}$$

$L_{xy}(x, y = a, b, c)$ is the mutual inductance between three-phase windings, p is the differential operator. Ignoring the salient pole effect of the rotor, L_{aa}=L_{bb}=L_{cc}=L,L_{xy}=M,there is no neutral line and the excitation self-inductance second harmonic can be ignored.therefore:ia+ib+ic=0, $Mi_b + Mi_c = -Mi_a$.

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + p \begin{bmatrix} L_s & 0 & 0 \\ 0 & L_s & 0 \\ 0 & 0 & L_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{2}$$

Where $L_s = L - M$.

The state equation :

$$p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1/L_s & 0 & 0 \\ 0 & 1/L_s & 0 \\ 0 & 0 & 1/L_s \end{bmatrix} \cdot \left\{ \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} - \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \right\} \tag{3}$$

The back EMF(Electromotive force) waveform and current waveform of brushless DC motor under 120 degree conduction mode of three phase six-state are shown in Figure 2.

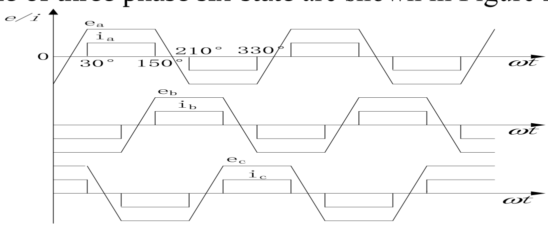

Figure 2. BLDCM back EMF and current waveform

The stator winding current interacts with the magnetic field generated by the rotor permanent magnet to generate electromagnetic torque.

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega} \tag{4}$$

According to Figure 2, if phases A and B are turned on,

$e_a = -e_b = E$， $e_c = 0$， $i_a = -i_b = I$， $i_c = 0$，

$$T_e = \frac{2EI}{\omega} \tag{5}$$

3. Commutation torque ripple analysis of BLDCM

When the motor operated in the three-phase six-state 120 °conduction mode, only two-phase windings are turned on at any time. Assume that phases A and C are turned on. $i_a + i_b + i_c = 0$, $E_a = E_b = -E_c = E_m$,the ideal electromagnetic torque of the motor is:

$$T_e = \frac{2E_m I}{\Omega} \tag{6}$$

When commutating,the motor converted from the two-phase windings of A and C to B and C.The current of A-phase winding is freewheeled by diode D4;the current of C-phase winding will gradually increase to a stable value.
Ignoring the influence of stator winding,

$$\begin{cases} L\frac{di_a}{dt} + Ri_a + E_a - \left(L\frac{di_c}{dt} + Ri_c + E_c \right) = 0 \\ L\frac{di_b}{dt} + Ri_b + E_b - \left(L\frac{di_c}{dt} + Ri_c + E_c \right) = U_d \end{cases} \tag{7}$$

Assuming that the values of the winding current of each phase are steady-state values, the current and electromagnetic torque of each phase winding are respectively:

$$\begin{cases} i_a = I - \frac{U_d + 2E_m}{3L} t \\ i_b = \frac{2(U_d - E_m)}{3L} t \\ i_c = -I - \frac{U_d - 4E_m}{3L} t \end{cases} \tag{8}$$

$$T_e = \frac{2E_m}{\Omega} \left(I + \frac{U_d - 4E_m}{3L} t \right) \tag{9}$$

From (9), t_{on} of the conduction phase winding and t_{off} of the off-phase winding during the commutation are respectively:

$$\begin{cases} t_{on} = \frac{3LI}{U_d + 2E_m} \\ t_{off} = \frac{3LI}{2(U_d - E_m)} \end{cases} \tag{10}$$

The key to suppressing the commutation torque ripple is to make the rising rate of the conduction phase current equals to the falling rate of the shutdown phase current[5-6],

$$U_d = 4E_m \tag{11}$$

It can be known that the commutation time in the commutation process is related to the back EMF, and the back EMF is proportional to the motor speed,the current variation law during BLDCM commutation at different speeds as shown in Figure 3:

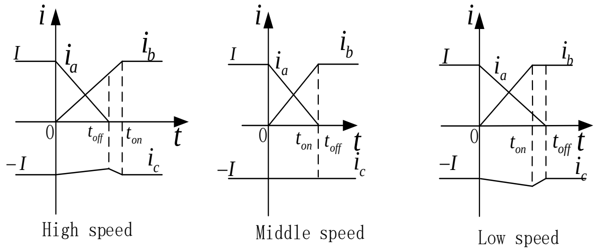

Figure 3. Variation of commutation current at different speeds

When $U_d < 4E_m$, when i_a has dropped to 0, i_b has not reached the steady-state value, as shown in high speed. The torque ripple can be obtained as:

$$T_e = \frac{2E_m I_0}{\Omega} \cdot \frac{U_d - 4E_m}{U_d + 2E_m} \tag{12}$$

When $U_d > 4E_m$,before i_a has dropped to 0, i_b has reached the steady-state value, as shown in middle speed. The torque ripple can be obtained as:

$$T_e = \frac{2E_m I_0}{\Omega} \cdot \frac{U_d - 4E_m}{U_d - E_m} \tag{13}$$

When $U_d = 4E_m$,when i_a falls to 0, i_b reaches a stable value,as shown in middle speed.The torque remains constant during the commutation process:

$$T_e = \frac{2E_m I_0}{\Omega} \tag{14}$$

It is the inconsistency of the change rate of the current between the turn-off phase and the conduction phase that causes the current fluctuation in the constant conduction phase and the fluctuation of the commutation electromagnetic torque. When commutation, the DC bus voltage should satisfy the relation $U_d = 4E_m$, and the back EMF is directly proportional to the motor speed.

4. Torque ripple suppression method based on Cuk converter

The topology of the Cuk circuit is shown in Figure 4.Control the power switching tube Q by PWM chopping.By adjusting the difference of the duty ratio D,the DC buck-boost can be realized[7].

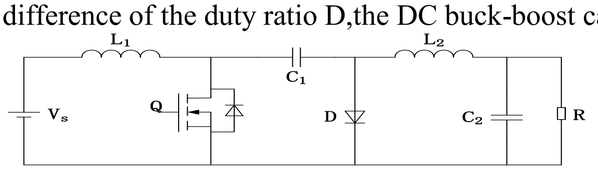

Figure 4. Cuk converter

When $T_{on} = DT_s$,the diode D is turned off. the DC power supply V_s charges the inductor L1 via the power switch tube Q.

$$V_{L1} = L_1 \frac{di_{L1}}{dt} = V_s \tag{15}$$

$$\Delta i_{L1+} = \frac{V_s}{L_1} DT_s \tag{16}$$

C_1 charges C_2 through the switch tube and discharge to the load and the inductor L2.

$$V_{L2} = L_2 \frac{di_{L2}}{dt} = V_{C1} - V_O \tag{17}$$

$$\Delta i_{L2+} = \frac{V_{C1} - V_O}{L_2} DT_s \tag{18}$$

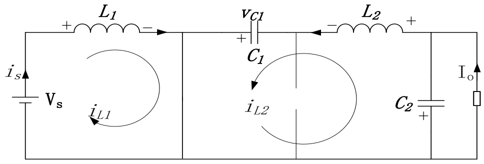

Figure 5. Switching tube Q conduction equivalent circuit

When $T_{off} = (1-D)T_s$, D is forward conducting.Since the inductor current cannot be abruptly changed,when the switch Q is turned off,L1 charges the C1 through D,

$$V_{L1} = L_1 \frac{di_{L1}}{dt} = V_s - V_{C1} \tag{19}$$

$$\Delta i_{L1-} = \frac{V_{C1} - V_s}{L_1} (1-D)T_s \tag{20}$$

At the same time,the current of L2 is supplied to the load through D,

$$V_{L2} = L_2 \frac{di_{L2}}{dt} = -V_O \tag{21}$$

$$\Delta i_{L2-} = \frac{V_O}{L_1} (1-D)T_s \tag{22}$$

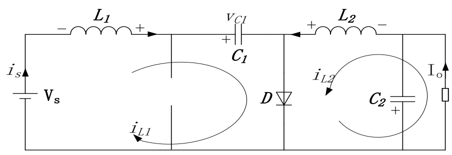

Figure 6. Switching tube Q cutoff equivalent circuit

When the circuit works in a stable operation,the increase of the inductor current in one switching cycle equals to the amount of reduction.

$\Delta i_{L1+} = \Delta i_{L1-}$, $\Delta i_{L2+} = \Delta i_{L2-}$.

$$V_{C1} = \frac{1}{1-D} V_s \tag{23}$$

$$V_O = DV_{C1} \tag{24}$$

$$V_O = \frac{D}{1-D} V_s \tag{25}$$

From (25), by adjusting the duty ratio , the output voltage V_o of the Cuk circuit can be controlled.And the motor back EMF is proportional to the speed:

$$E_m = k_e n$$

(26)

When the power switch Q is turned on,the relationship between duty cycle and speed is:

$$D = \frac{4k_e n}{V_s + 4k_e n}$$

(27)

It can be seen that the torque ripple generated by the commutation can be suppressed by adjusting the duty ratio D of the Cuk pre-stage conversion circuit.

5. Simulation results and analysis

In order to verify the feasibility of the proposed method,a system simulation model was established on the MATLAB/Simulink simulation platform.The simulation model system is shown in Figure 7.

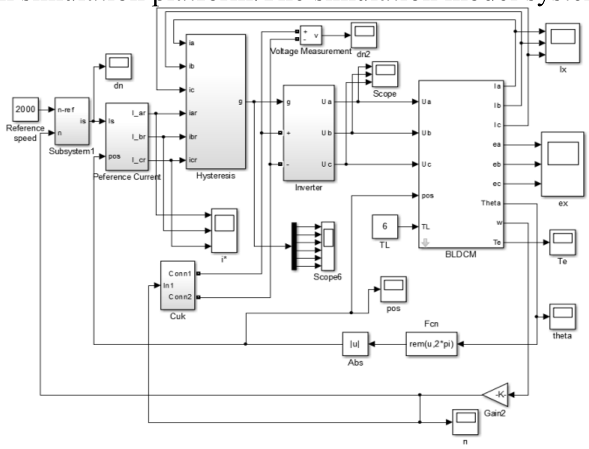

Figure 7. Simulation Model system

The motor load torque is $6N \cdot m$ .When the motor speed is 2000r/min,the bus voltage is 48V. When the front stage conversion circuit is not compensated,the bus voltage waveform,the A phase current waveform and the output torque are shown in the following Figures.

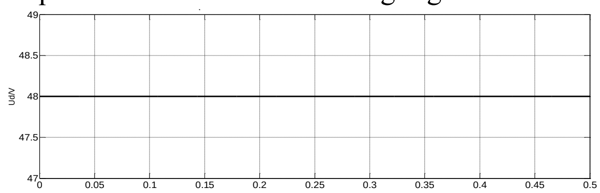

Figure 8. Bus voltage when uncompensated

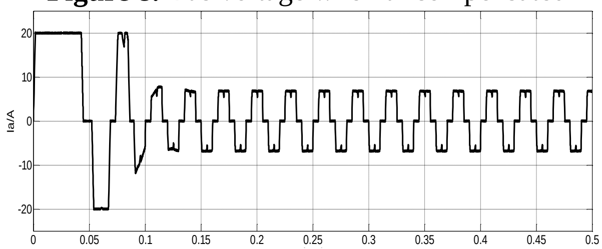

Figure 9. Phase A current waveform without compensation

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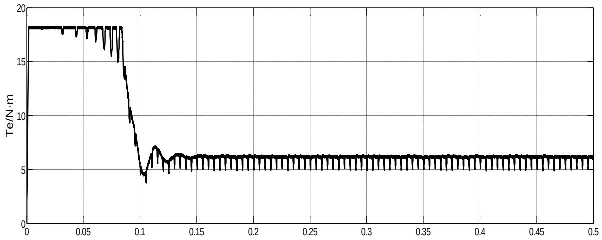

Figure 10. Torque waveform without compensation

After increasing the compensation , the bus voltage increased to 60V,

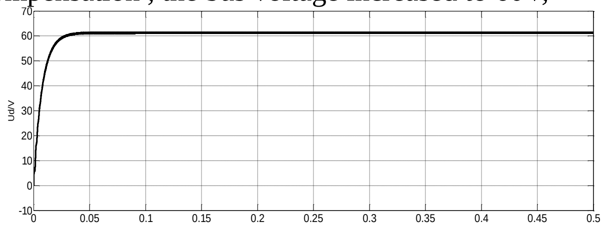

Figure 11. Bus voltage after Cuk conversion compensation

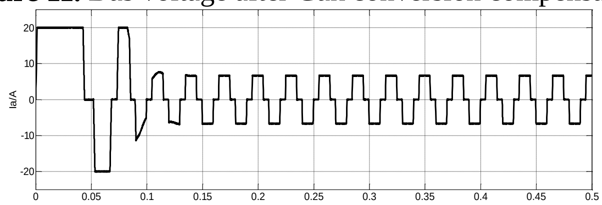

Figure 12. Phase A current waveform after compensation

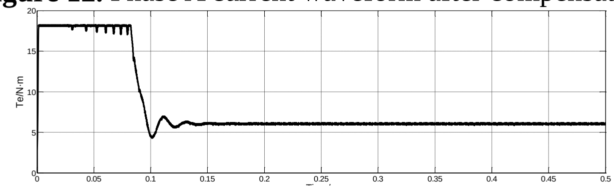

Figure 13. Compensated torque waveform

Comparing the above figures, it can be seen that the pulsation of the flat top portion of A-phase current is suppressed,and the corresponding output torque is smooth, the torque ripple is effectively suppressed.

6. Conclusion

In this paper,the mathematical model of BLDCM and the reason of commutation torque ripple are analyzed.A method combining Cuk converter and power inverter circuit is proposed.By changing the bus voltage,realize torque ripple suppression at full speed.The simulation is verified on the MATLAB platform and the results show the effectiveness of the proposed method.

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