Research for SVPWM Control Method of Brush-less DC Motor Using Z-source Converter

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Abstract. A novel brush-less DC motor SVPWM control method based on Z-source converter is proposed in this paper. The proposed method can increase speed range by utilizing the shoot-through state to boost the DC voltage and also has the advantage of high stability, small torque ripple, high efficiency and low noise, effectively solving the problem of small speed range, large torque ripple and poor stability of existing control system. A novel mathematical model is also derived for motor control. With the algorithm simulation advantage of MATLAB and the circuit structure simulation advantage of PSIM, The united simulation results of MATLAB and PSIM are analyzed in detail.

Introduction

Recently, brushless DC (BLDC) motor has been widely used in electric vehicles since it possesses the merits of high efficiency, high power density, high torque to inertia ratio and long life. However, with the increasing requirements of application in practice, it is desirable to minimize torque ripple and maximum speed range in a BLDC drive. And, it becomes a key issue to introduce a system that can obtain small torque ripple and wide speed range, which requires an urgent solution. As a result, worldwide more attention is paid to the driving method with less torque ripple and wider speed range. The reasons why the torque ripple is generated are detailedly discussed based on the mathematical model of BLDCM in [1, 2], which certificate that the torque ripple can be up to 50% of average torque. On a base of the comparison between three-three and two-two conduction modes, a new method to reduce torque ripple that is proposed, which achieves good performance in reducing torque ripple [1, 2]. However, how to improve the speed performance is not mentioned in these two papers. In [3], by putting the Z-source network into motor drive system, a novel motor drive circuit is presented, where Z-source network is connected to motor drive system to boost the DC side voltage and reduce the torque ripple when the circuit commutates. Similarly, this complicated circuit does little benefit to the performance of motor speed, and it needs additional five switching tubes, leading to the high cost and complex control method [4, 5] also adopt two-two conduction mode, and additionally, the 3rd switching tube is turned on to get Z-source in a straight state and boost DC side voltage, which can guarantee good speed performance of motor drive system, but, meanwhile, lead to large torque ripple, restricting its application in practice.

A method similar to vector control is put forward to control BLDC motor in [6, 7], which reduces the torque ripple obviously and belongs to three-three conduction mode. Nonetheless, in this method, it needs to insert dead time to avoid the upper and lower bridge arm shorting, otherwise, which can result in burning the switching tubes and get the system unstable. And how to raise the speed performance is also not mentioned in both papers.

In this paper, a novel BLDC motor drive method is proposed in view of the key point which puts a Z-source convertor into use. The presented control system not only avoids the above existing drawbacks, but also shows the following virtues. Beginning with, the unique feature of boosting the voltage belonging to Z-source network is utilized to enhance DC bus voltage, which enlarges the speed range and improves the speed performance. Next, the DC bus voltage can be rapidly stabilized in the case that the battery voltage drops abnormally. Also, the inverter bridge can be made in shoot-through state via getting the switching tubes turned on earlier and delayed to be off, without
any influence on the normal motor driving and the original switching frequency. Then, there is no dead time of Inverter Bridge, good for stabilizing the control system. Additionally, the torque ripple of motor is suppressed to less than 10% by using the SVPWM vector control method, obviously improving torque performance and system efficiency.

Circuit Topology

![Circuit Diagram](image)

Figure 1. Topology of the main circuit.

The circuit configuration of proposed motor drive system, as shown in Fig. 1, consists of DC power, Z-source network, three-phase bridge and BLDCM. Switching tube \( Q \) is used for avoiding that the system works in abnormal mode\[8\], and is off in case of the short circuit of three-phase bridge, otherwise is on the contrary. Two inductors \( L_1, L_2 \), and two capacitors \( C_1, C_2 \), where \( L_1 \) equals to \( L_2 \) and \( C_1 \) equals to \( C_2 \), make up Z-source network that is used for boosting and stabilizing the voltage. The DC bus voltage can be raised up by adjusting the time of shoot-through state of any three-phase bridge arm to an appropriate size once the DC voltage drops to a certain size that cannot meet the need of motor driving. And the station that the upper and lower switching tubes of the same bridge arm are simultaneously conducted is allowed, which means there are no dead time and little torque ripple. The boosted DC bus output voltage \( V_{pu} \), in Z-source network, can be expressed as\[9\]

\[
V_{pu} = \frac{V_{dc}}{1 - 2D_0},
\]

(1)

where \( D_0 \) is shoot-through duty cycle, \( V_{dc} \) is DC input voltage. \( D_0 \) can be calculated as

\[
D_0 = \frac{t_0}{T_s},
\]

(2)

where \( T_s \) is switching cycle, \( t_0 \) is shoot-through time in a switching cycle.

Working Principle Analysis

The key point of Z-source network, firstly proposed by professor Fangzheng Peng in Michigan State University of USA, is to adjust the time of shoot-through state of any three-phase bridge arm to an appropriate size in order to effectively boost the DC bus voltage. Through the combination of the advantages of Z-source network and SVPWM control strategy, the switching tubes are turned on earlier and delayed to be off to get the whole circuit system in shoot-through state where only one phrase is shorted and the switching frequency stays same.

The three kind of operating states of proposed control system are in detail presented in Fig. 2, which are respectively Working States of Effective Vector, Traditional Zero Vector and Shoot-through Zero Vector. In Fig. 2. (a), as effective vector acts on BLDCM, the switching tubes \( Q_1, Q_2, Q_3 \) and \( Q_7 \) are on, and then, the higher DC bus voltage is caused by Z-source network to drive the motor, where energy from the DC side flows into three-phase windings of motor.

In Fig. 2. (b), the being-off of \( Q_2 \) and the being-on of \( Q_5 \) means the BLDCM works in the state of traditional zero vector, the DC bus voltage is still boosted by Z-source, but there is no energy from DC side injected into motor of which the current of three-phase windings freewheels into \( Q_1, Q_4 \) and \( Q_5 \). If, in Fig. 2. (b), \( Q_2 \) is delayed to be off, \( Q_7 \) is directly turned off, and \( Q_5 \) is turned on normally, the three-phase inverter bridge circuit is in the state of shoot-through shown in Fig. 2. (c). During the
period of inverter bridge circuit shoot-through, $Q_2$ and $Q_5$ is shorted together, the two inductors are charged by the stored energy in two capacitors among the Z-source to prepare for next boosting the voltage, also there is no energy injected into the motor from DC side, and additionally, the current of motor three-phase windings freewheels into $Q_1$, $Q_2$, $Q_3$, and $Q_6$.

The proposed system has three working state as shown in Fig. 2. Fig. 2 (a) shows the state when effective vectors work. $Q_1$, $Q_2$, $Q_3$, and $Q_7$ turn on, DC bus voltage that outputs from Z-source network provides DC power for BLDCM, which makes the motor works in higher speed. When $Q_2$ turns off, $Q_3$ turns on, the motor enters into the conventional zero vector working state as shown in Fig. 2 (b). In this state, DC bus voltage still be high but this DC power can not flow into the motor. Three phase winding current freewheel through $Q_1$, $Q_3$, and $Q_5$. If $Q_2$ delays turning off at the time of $Q_3$ turns on, shoot-through working state can be gotten as Fig. 2(c) shows. In this state, $Q_3$ turns off, $Q_2$ and $Q_5$ make the bridge shorted, the capacitor in Z-source network charge the inductor to prepare for the next step-up. Also the DC power does not flow into the motor. Three phase winding current freewheel through $Q_1$, $Q_2$, $Q_3$, and $Q_6$.

![Figure 2. Operation stages of the system circuit.](image)

This shows that the DC power does not flow into the motor in conventional zero vector working state and shoot-through working state. Three phase winding current both freewheel through switching tubes. Thus shoot-through vectors can be inserted instead of part of conventional zero vectors but effective vectors are still kept unchanged. Then not only Z-source network can boost the DC input power, but also the motor can be driven normally. The specific method is shown in Fig. 3. Shoot-through vector is inserted to every phase at the time of switching commutation by using the method of turning-on in advance and turning-off delay. The shoot-through vector distributes in every phase averagely to balance the switching loss. Fig. 3 only shows one phase that is inserted shoot-through vector. The other phases are similar with Fig. 3.

![Figure 3. Insert of the shoot-through state.](image)
Control Strategy

Research shows that sine wave driving method is more effective than square wave driving method in suppressing torque ripple[10]. Vector control method is optimal in sine wave driving method. In this paper, vector control method is used and a novel mathematical model is derived for motor vector control.

The control strategy is shown in Fig. 4. It makes the system switch between the boost control and the motor control, which can both adjust the system’s DC bus voltage and control the motor speed and torque.

![Figure 4. Vector control system of BLDCM.](image)

In Fig. 4, \( V_{pm}^* \) is reference value of peak DC bus voltage, \( V_{pm} \) is actual peak DC bus voltage. When three phase bridge is shorted, \( V_{pm} \) drops to zero. When three phase bridge works regularly, \( V_{pm} \) is not zero. So it is hard to detect \( V_{pm} \) directly. Research shows that[11] \( V_{pm}^* = 2V_r - V_{dc} \), so \( V_{pm} \) can be calculated by detecting capacitor voltage \( V_c \) and DC power \( V_{dc} \). \( D_0 \) is controlled by the difference between \( V_{pm}^* \) and \( V_{pm} \), and DC bus voltage \( V_{pm} \) is controlled by \( D_0 \). Thus a closed loop for DC bus voltage is realized in this control system.

Now a novel mathematical model for speed and torque control will be derived. Three phase EMF mathematical models should be calculated firstly.

![Figure 5. Rotor position and the flux density distribution curve.](image)

Fig. 5 shows the distribution curve of flux density when the rotor position angle is \( \theta \). Fig. 5 (a) assumes that motor rotates counter-clockwise and the real-time position angle is \( \theta \). Fig. 5 (b) shows the corresponding flux density curve when motor rotates counter-clockwise. From Fig. 5 (b) the function of flux density curve \( B(x) \) can be written as

\[
B(x) = \begin{cases} 
B_n \left( \frac{6}{\pi} x + 3 \right) & \frac{\pi}{2} \leq x \leq \frac{\pi}{3} \\
B_n & \frac{\pi}{3} < x \leq \frac{2\pi}{3} \\
-B_n \left( \frac{6}{\pi} x - 9 \right) & \frac{2\pi}{3} < x \leq \frac{3\pi}{2} \\
B_n & \frac{3\pi}{2} < x \leq \frac{4\pi}{3} \\
-B_n \left( \frac{6}{\pi} x - 9 \right) & \frac{4\pi}{3} < x \leq \frac{5\pi}{2} 
\end{cases}
\]

(6)
where \( B_m \) is the magnitude of magnetic flux density which maintains 120° electrical angle. Obviously \( B(x) \) is a periodic function with period \( 2\pi \). That is \( B(x + \pi) = -B(x) \). EMF \( e_r \) and permanent magnet flux linkage \( \psi_{pm}(\theta) \) of phase A can be written as

\[
e_r = \frac{d\psi_{pm}(\theta)}{dt} \quad (7)
\]

\[
\psi_{pm}(\theta) = N\phi_{pm}(\theta) = N \int_{\frac{\pi}{2}}^{\frac{\pi}{2} + \theta} B(x) S dx \quad (8)
\]

where \( N \) is winding turns of phase A, \( \phi_{pm}(\theta) \) is permanent magnet flux of phase A when real-time position angle is \( \theta \). \( S \) is the area which is surrounded by windings in the inner surface of the stator.

From Eq. 7 and Eq. 8, Eq. 9 can be written as

\[
e_r = \omega_r \psi_{pm}(\theta + \frac{\pi}{2}) \quad (9)
\]

where \( \omega_r = \frac{d\theta}{dt} \), represents rotor electrical angular speed. \( \psi_{pm} = 2NSB_m \) is flux linkage magnitude of phase A. Similarly EMF of phase B and C can be written as

\[
e_r = -\omega_r \psi_{pm}(\theta + \frac{\pi}{6}) \quad (10)
\]

\[
e_r = -\omega_r \psi_{pm}(\theta + \frac{5\pi}{6}) \quad (11)
\]

Define Park transformation matrix \( M_p = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \), \( M_p^{-1} \) represents its inverse matrix. Define Clarke transformation matrix \( M_c = \frac{2}{3} \begin{bmatrix} 1 & 1 & 1 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \), \( M_c^{-1} \) represents its inverse matrix. Torque of BLDCM is expressed as

\[
T_e = \frac{e_r}{\Omega} \begin{bmatrix} i_a + e_r i_a + e_r i_a \\ i_b + e_r i_b + e_r i_b \end{bmatrix} \quad (12)
\]

where \( \Omega \) is mechanical angular speed, \( i_a, i_b, i_c \) are three phase currents. Three phase currents can be converted to d-q coordinate system through Clarke and Park. Then from Eq. 9,10,11, Eq. 12 can be rewritten as

\[
T_e = \frac{1}{\Omega} \begin{bmatrix} \psi_{pm}(\theta + \frac{\pi}{2}) \cos \phi_{pm} B(\theta + \frac{\pi}{6}) \sin \phi_{pm} B(\theta + \frac{\pi}{6}) + \sin(\theta + \frac{\pi}{6}) \phi_{pm} B(\theta + \frac{5\pi}{6}) \end{bmatrix} i_a \\
+ \frac{1}{\Omega} \begin{bmatrix} \psi_{pm}(\theta + \frac{\pi}{2}) \cos \phi_{pm} B(\theta + \frac{\pi}{6}) \sin \phi_{pm} B(\theta + \frac{\pi}{6}) - \sin(\theta + \frac{\pi}{6}) \phi_{pm} B(\theta + \frac{5\pi}{6}) \end{bmatrix} i_b \\
+ \psi_{pm} \begin{bmatrix} \cos \phi_{pm} B(\theta + \frac{\pi}{2}) \sin(\theta + \frac{\pi}{3}) B(\theta + \frac{\pi}{6}) + \sin(\theta + \frac{\pi}{3}) B(\theta + \frac{5\pi}{6}) \end{bmatrix} i_c \quad (13)
\]

where \( \omega_r = p\Omega \), Eq. 13 can be simplified as

\[
T_e = p\psi_{pm} \begin{bmatrix} \cos \phi_{pm} B(\theta + \frac{\pi}{2}) \sin(\theta + \frac{\pi}{6}) B(\theta + \frac{\pi}{6}) + \sin(\theta + \frac{\pi}{6}) B(\theta + \frac{5\pi}{6}) \end{bmatrix} i_a \\
+ p\psi_{pm} \begin{bmatrix} \cos \phi_{pm} B(\theta + \frac{\pi}{2}) \sin(\theta + \frac{\phi}{3}) B(\theta + \frac{\pi}{6}) - \sin(\theta + \frac{\phi}{3}) B(\theta + \frac{5\pi}{6}) \end{bmatrix} i_b \\
+ p\psi_{pm} \begin{bmatrix} -\sin \phi_{pm} B(\theta + \frac{\phi}{2}) \sin(\theta + \phi/3) B(\theta + \phi/6) \sin(\theta + \phi/3) B(\theta + \phi/6) \end{bmatrix} i_c \quad (14)
\]
If $i_q = 0$, then Eq. 14 is expressed as

$$i_q = \frac{\tau}{p\psi_m} - \sin \theta (\theta + \frac{\pi}{6}) - \sin \theta (\theta + \frac{\pi}{3}) B(\theta + \frac{\pi}{6}) - \sin \theta (\theta - \frac{\pi}{3}) B(\theta + \frac{5\pi}{6}).$$ \hspace{1cm} (15)

In this paper, $i_q = 0$ control strategy is adopted. The value of $i_q$ can be calculated off-line at different speed and torque according to Eq. 14, then stored in the control system. $i_q = 0$ makes the system simplify to control $i_q$ only, which will suppress torque ripple obviously. The specific control method is shown in Fig. 4. The complete system has four controllers, which are: speed controller, $i_d$ controller, $i_q$ controller and voltage controller for peak dc link voltage control. Speed controller outputs $i_q^*$, which is given $i_q$ controller.

If the DC voltage cannot satisfy the requirement of high reference speed, as dotted line shown in Fig. 4, the reference DC bus voltage $v_{pn}^*$ can be increased properly, which will adjust $D_p$ to obtain the acquired DC bus voltage $v_{pn}$ to improve motor speed through the voltage controller.

**Simulation Results and Analyses**

In order to verify the proposed control strategy, as shown in Fig. 6, a united simulation model is carried out by using MATLAB/ SIMULINK and PSIM software with a 260W BLDC motor. Fig. 6 (a) shows the simulation model in PSIM, which is the main circuit of the proposed system. Fig. 6 (b) shows the simulation model in MATLAB, which is the main control method of the proposed system. SimCoupler in Fig. 6 (b) connects MATLAB and PSIM.

![Simulation model in PSIM](image1)

(a) Simulation model in PSIM

![Simulation model in MATLAB](image2)

(b) Simulation model in MATLAB

Figure 6. Simulation Fig. of the system.

The simulation parameters are as follows: $L_d = L_q = 1\text{mH}$, $C_i = C_2 = 600\mu\text{F}$, stator resistor $R_s = 2.875\Omega$, stator inductor $L_s = 8.5\text{mH}$, pole number $P = 4$, input power voltage $U_{dc} = 48\text{V}$, rated speed $n = 1000\text{r/min}$, moment of inertia $J = 0.001\text{kg} \cdot \text{m}^2$, output torque $T = 2.5\text{N} \cdot \text{m}$, switching cycle $T_s = 0.0001\text{s}$. To verify Z-source network can boost and stabilize DC bus voltage in voltage closed-loop, DC power drops from 45V to 35V suddenly at 0.15s while the reference DC bus voltage $v_{pn}^*$ is 48V. As Fig. 7 shows that DC bus voltage is boosted to 48V and also it can be quickly stabilized at 48V less than 0.1s when voltage drops at 0.15s.
Specific waveform of DC bus voltage is shown in the top right corner of Fig. 7 (b). It is a series of square wave with period $T$ and amplitude $V^{pu}$.  

Fig. 8 shows the comparison of speed and torque performance between conventional control method and Z-source control method. Conventional control method adopts two-two conduction mode. Both system have the same parameters: DC supply power $U_{dc} = 48V$, rated speed $n = 1000r/min$, output torque $T = 2.5N\cdot m$. Fig. 8 (a) shows that Z-source control method proposed in this paper has faster speed response. Fig. 8 (b) shows that torque ripple in Z-source vector control system is suppressed less than 10% of the average torque, much less than conventional control method.

Fig. 9 shows the speed performance of the proposed system. The reference speed increases to 2500r/min from 500r/min at 0.1s while the reference DC bus voltage changes from 48V to 150V at 0.2s. As shown in Fig. 9, motor speed stops increasing at about 1200 r/min as the DC bus voltage 48V can not satisfy reference speed 2500r/min at 0.1s. When the reference DC bus voltage increases to 150V at 0.2s, as shown in Fig. 9 (a), the DC bus voltage increases to 150V after about 0.13s voltage boosting process. The motor speed increases to the set speed 2500 r/min smoothly in Fig. 9 (b) as DC bus voltage becomes higher that shows in Fig. 9 (a). So the proposed system has wider speed range and better speed performance as shown in Fig. 9.

Conclusions

A novel BLDC motor drive method based on a Z-source convertor is proposed in this paper. Circuit operation and simulation results are analysed in detail which verify the following conclusions. Using the method of turning-on in advance and turning-off lingeringly to insert shoot-through state guarantees the normal drive of BLDCM, and less switching loss. The system becomes more stable without inserting dead time. The motor can still work normally because of Z-source when the battery voltage or DC power supply voltage drops suddenly. The proposed system has wider speed range and
better speed performance. SVPWM vector control method makes the torque ripple lower than 10% of the average torque, which improves torque performance and system efficiency obviously.

References


