Application of Z-source Inverter for Permanent-magnet Synchronous Motor Drive System for Electric Vehicles

LIU Ping*, LIU He-ping

State Key Laboratory of Power Transmission Equipment & System Security and New Technology, Chongqing University, Chongqing, 400044, China

Abstract

This paper presents a novel permanent-magnet synchronous motor (PMSM) drive system with bidirectional Z-Source inverter (ZSI) for electric vehicles, and a modified vector controlled scheme of the PMSM drive is developed by considering DC-link voltage boosting. Characteristics of ZSI are used for DC-link voltage control in a single stage to obtain wide speed range of PMSM instead of field weakening control. Several simulation results obtained in Saber verify the feasibility and effectiveness of the proposed system.

Keywords: Permanent-magnet synchronous motors; Electric vehicles; Z-Source inverter; Voltage boost

1. Introduction

Due to the drastically increasing price of oil and the growing concern about global environment problems, more and more attention is being paid to research on electric vehicles (EV), which are much more environmentally friendly.

It is necessary for the drive system of EV to have wide operation range that is from stand still to high speed running. Although motors with different structures have been used to propel the vehicles, the permanent magnet synchronous motors (PMSM) have become more and more attractive because of their high efficiency, high power density, and high reliability [1-2]. However, these motors inherently have a short constant-power region due to their rather limited field weakening capability. In order to increase the speed range, two main control schemes have been discussed in past works. The most popular one is the field weakening control in the high-speed region [1], but it needs additional current to reduce the magnet flux of the motor. The other one is a DC-link voltage control method. In references [3]-[4], PMSM drive system with a boost converter in series with the PWM inverter to change the DC-link voltage above the rated speed has been discussed. However, this two-stage system increases not only the complexity of circuitry and control but also the cost and the space requirement. Meanwhile there are several defects in the traditional voltage source inverter.

A new type of single-stage power converter, Z-Source inverter (ZSI), has been proposed as a competitive alternative to existing inverter topologies [5-7]. Due to the obvious inherent advantages such as both voltage buck and boost capabilities, it has been adopted for various applications, such as fuel cell energy conversion systems [5] and induction motor drives [6].

In this paper, a complete PMSM drive system with bidirectional ZSI has been proposed. Then, the steady state operating principle of ZSI, the voltage boosting control scheme and modified vector controlled scheme for the PMSM drives are presented. To verify the proposed system, simulation studies using Saber are performed.

* Corresponding author. Tel.: +086-023-65105208; fax: +086-023-65105208.
E-mail address: lp1481@gmail.com.
2. Bidirectional Z-Source Inverter

Fig. 1 shows the configuration of the proposed drive system, which consists of a battery pack, an impedance network, a conventional voltage-source inverter and a PMSM. The impedance network consists of two identical inductors and two identical capacitors connected in a specific manner to achieve the desired properties. The additional switch S7 is installed antiparallel to the input diode to eliminate the undesirable operation modes caused by inductor current discontinuous, and enables the system have the ability of bidirectional power flow.

![Fig. 1 Topology with bidirectional ZSI for PMSM drive](image)

From the two equivalent circuits of the ZSI shown in Fig. 2, we have \( I_{L_i} = I_{L_z} \) and \( V_{C_1} = V_{C_z} \).

As described in [5], in the steady state, the operating principle can be expressed as follows:

\[
\begin{align*}
B &= 1 / (1 - 2D_0) \\
V_{dc} &= V_c / (1 - D_0) = B V_{in} \\
V_c &= (1 - D_0) B V_{in} \\
\overline{V_{dc}} &= D_0 \overline{0} + (2V_c - V_{in})(1 - D_0) = V_c
\end{align*}
\]

Where \( D_0 \) is the shoot-through time duty ratio. \( B \) is the boost factor resulting from the shoot-through zero state. \( V_{in} \) is the dc source voltage. \( V_{dc} \) is the peak DC-link voltage across the inverter bridge. \( \overline{V_{dc}} \) is the average dc-link voltage, which equals to the capacitor voltage.

In order to use shoot-through vector to control the dc boost of this inverter, PWM methods are modified and discussed comprehensively: simple, maximum boost, maximum constant boost control, and modified SVPWM scheme (MSVPWM). SVPWM technique is possibly the best among all the PWM techniques for variable speed applications because of lower current harmonics and a higher modulation index. So the MSVPWM [7] scheme is adopted in this paper.

3. Drive System

3.1 Voltage and Current Limits [8]

For a PMSM, the steady state voltage equation in the rotor reference frame is

\[
\begin{align*}
\begin{bmatrix}
\dot{v}_{sd} \\
\dot{v}_{sq}
\end{bmatrix} &=
\begin{bmatrix}
R + p L_q & -\omega L_q \\
\omega L_d & R + p L_q
\end{bmatrix}
\begin{bmatrix}
i_{sd} \\
i_{sq}
\end{bmatrix}
+ \begin{bmatrix}
0 \\
\omega \lambda_{pm}
\end{bmatrix}
\end{align*}
\]

where \( v_{sd}, v_{sq}, i_{sd} \) and \( i_{sq} \) are d- and q-axis voltages and currents respectively, \( R, L_d, \) and \( L_q \) are motor armature resistance, d- and q-axis inductances respectively, \( \omega, \) and \( \lambda_{pm} \) are electrical angular frequency and PM flux linkage respectively. In practice, considering the motor maximum line current amplitude \( i_{s max} \) and maximum available voltage \( v_{s max} \), one can form the following constraints

\[
\begin{align*}
i_{sd}^2 + i_{sq}^2 &\leq i_{s max}^2 \\
v_{sd}^2 + v_{sq}^2 &\leq v_{s max}^2
\end{align*}
\]

Substituting (2) into (3), the derivative operator becomes zero in the steady state, and neglecting the armature resistance drop for high-speed operation, one can obtain an equivalent voltage constraint as

\[
(L_q i_{sq})^2 + (L_d i_{sd} + \lambda_{pm})^2 \leq \frac{v_{s max}^2}{\omega e^2}
\]

Generally, as the DC-link voltage of inverter keeps constant, \( v_{s max} \) will also keep constant. As \( \omega_e \) is larger than the rated speed of motor, a field weakening strategy should be used to provide the motor a high speed...
operation as the constant $v_{\text{max}}$ is used. However, the corresponding current amplitude will increase such that the copper loss will increase. From (4), in this paper, another strategy is used to provide the motor a high speed operation by boosting the $v_{\text{max}}$ as $\omega_1$ is increased.

Having considered the characteristics of battery, the battery current is limited to the value $I_{BT\text{max}}$. This value corresponds to the DC-link current when the motor current is the rated current. Because of this battery current limit, the system operates with constant torque within the rated speed and operates with constant power above the rated speed. The maximum output torque is defined as the following equation

$$T_{\text{max}} = E_{BT} I_{BT\text{max}}/(\omega_1 \eta) \quad (5)$$

Where $E_{BT}$ is the battery voltage, and $\eta$ is the convention efficiency.

3.2 Control Scheme

Fig.3 shows the control scheme of PMSM drive system with bidirectional ZSI for EV.

![Fig.3 Control scheme of PMSM drive system with ZSI for EV](image)

The $i_{sq}$ bound calculator functional block diagram of Fig.3 shows in Fig. 4(a). The input parameter is the rotor speed and the output is maximum amplitude of q-axis current $i_{sq\text{max}}$. In the speed PI controller, it will limit the motor maximum line current amplitude in the zero d-axis current control mode such that the battery current will not exceed its limit.

The DC-link voltage command block is shown in Fig. 4(b). When the rotor speed $\omega_1$ is less than the rated speed $\omega_b$, the ZSI works without boost and the DC-link voltage command $v_{dc}'$ equals to the input voltage. The $v_{dc}'$ increases above the rated voltage as the motor in the high speed operation.

The DC-link voltage is unsuitable to select as a feedback signal due to the shoot-thought state of ZSI. By equation (1), the Z-source capacitor voltage $V_C$ can be boosted by controlling the shoot-through time duty ratio $D_0$. So in this paper, $V_C$ is selected as feedback signal to control $V_{dc}$ indirectly. In order to overcome the nonlinear problem between $V_{dc}$ and $V_C$, a linear capacitor voltage controller [9] is adopted. The task of shoot-through controller in Fig.3 is to generate $D_0$. 

The DC-link voltage command block is shown in Fig. 4(b). When the rotor speed $\omega_1$ is less than the rated speed $\omega_b$, the ZSI works without boost and the DC-link voltage command $v_{dc}'$ equals to the input voltage. The $v_{dc}'$ increases above the rated voltage as the motor in the high speed operation.

The DC-link voltage is unsuitable to select as a feedback signal due to the shoot-thought state of ZSI. By equation (1), the Z-source capacitor voltage $V_C$ can be boosted by controlling the shoot-through time duty ratio $D_0$. So in this paper, $V_C$ is selected as feedback signal to control $V_{dc}$ indirectly. In order to overcome the nonlinear problem between $V_{dc}$ and $V_C$, a linear capacitor voltage controller [9] is adopted. The task of shoot-through controller in Fig.3 is to generate $D_0$. 

The DC-link voltage is unsuitable to select as a feedback signal due to the shoot-thought state of ZSI. By equation (1), the Z-source capacitor voltage $V_C$ can be boosted by controlling the shoot-through time duty ratio $D_0$. So in this paper, $V_C$ is selected as feedback signal to control $V_{dc}$ indirectly. In order to overcome the nonlinear problem between $V_{dc}$ and $V_C$, a linear capacitor voltage controller [9] is adopted. The task of shoot-through controller in Fig.3 is to generate $D_0$.
4. Simulation Results

Table 1. Values of parameters

| Component          | Parameter                  | Value          |
|--------------------|----------------------------|----------------|
| PMSM               | Rated output power         | 17 kW          |
|                    | Rated speed                | 50 rad/s       |
|                    | Rated torque               | 340 N.m        |
|                    | Armature resistance (R)    | 0.4375 Ω       |
|                    | Pole number                | 8              |
|                    | d-axis inductance (L_d)    | 8 mH           |
|                    | q-axis inductance (L_q)    | 8.5 mH         |
|                    | Flux of field              | 0.8 Wb         |
| Battery            | Rated voltage (E_BT)       | 410 V          |
|                    | Rated capacity             | 100 Ah         |
| Transmission system| ratio                      | 1:2            |
|                    | efficiency                 | 0.9            |
| Z-source network   | Inductor                   | 36.5 μH        |
|                    | Capacitor                  | 300 μF         |
| Vehicle            | Gross mass                 | 990 kg         |
|                    | Frontal area               | 1.7 m²         |
|                    | Rolling Resistance Coefficient | 0.015     |
|                    | Radius of wheels           | 0.287 m        |
|                    | Aerodynamic drag Coefficient | 0.3       |

The effectiveness and the dynamics of the proposed drive system for EV are investigated extensively in simulation using Saber. The values of the system parameters are listed in table 1. The system is operated in different operation modes, as shown in Fig. 5.
From Figs. 5 - 7, one finds the following.

- The d-axis current keeps zero above the rated speed. That is, the drive system does not need the current to reduce the magnet flux of the motor. Thus, no additional copper loss by the current is generated.
- In the regenerative braking mode, $i_{br}$ is negative. That is, the system has the ability of bidirectional power flow.
- As in the rated speed operation, the ZSI works without shoot-through and the DC-link voltage equals to the input voltage.
• When the motor speed is increasing or decreasing above the rated speed, the ZSI is in the voltage boost mode. The DC-link voltage is boosted in proportional to the speed by Fig.4. And the results of $B$, $D_0$, $V_c$ coincide with the analytical calculation by equation (1).

5. Conclusion

This paper has presented a PMSM drive system with bidirectional ZSI. In order to extend the speed range of the PMSM and decrease the current amplitude in the high speed region, the ZSI provides an increasing DC-link voltage by gating on both the upper and lower switches of the same phase leg, as the rotor speed is greater than the rated speed. Hence, the reliability of the inverter is greatly improved because the shoot through can no longer destroys the circuit. The drive system can provide a low cost and highly efficient single stage structure for reliable operation. In addition, the characteristics of the PMSM driven by bidirectional ZSI are analyzed. The simulated results are performed to verify the proposed system.

Acknowledgements

This work was supported by the Fundamental Research Funds for the Central Universities (CDJXS11150002).

References

[1] Z. Q. Zhu and D. Howe. Electrical Machines and Drives for Electric, Hybrid, and Fuel Cell Vehicles. *IEEE Proceedings*, vol. 95, no. 4, pp. 746-765, Apr. 2007.

[2] C. C. Chan. The State of the Art of Electric, Hybrid, and Fuel Cell Vehicles. *Proceedings of the IEEE*, vol. 95, pp. 704-718, 2007.

[3] K. Yamamoto, K. Shinohara, T. Nagahama. Characteristics of permanent-magnet synchronous motor driven by PWM inverter with voltage booster. *IEEE Trans. On Ind. Appl.*, Vol. 40, no. 4, pp.1145-1152, 2004.

[4] K. Yamamoto, K. Shinohara and S. Furukawa. Permanent Magnet Synchronous Motor Driven by PWM Inverter with Voltage Booster with Regenerating Capability Augmented by Double-Layer Capacitor. *IEEE Trans. IA*, Vol. 126, No.5, pp. 639-645, 2006.

[5] F. Z. Peng, X. M. Yuan, X. P. Fang, and Z. M. Qian. Z-source inverter for adjustable speed drives, *IEEE Power Electron. Lett.*, vol. 1, no. 2, pp. 33–35, Jun. 2003.

[6] D. W. Novotny and T. A. Lipo. *Vector Control and Dynamics of AC Drives*. New York: Oxford Univ. Press, 1997, ch. 9.

[7] T. Quang-Vinh, et al.. Algorithms for Controlling Both the DC Boost and AC Output Voltage of Z-Source Inverter. *IEEE Transactions on Industrial Electronics*, vol. 54, pp. 2745-2750, 2007.