Analysis and Control of Current Ripples of Z-Source Inverters

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ABSTRACT Load current ripple is an important issue in the design and control of inverters since it influences the torque ripple and noise amplitude of a motor drive. The current ripple of Z-source inverter (ZSI) is analyzed in this paper. The expression of current ripple is derived and the current ripples of ZSI and voltage-source inverter (VSI) are compared. A variable DC-link voltage and switching frequency method was adopted to reduce conduction and switching losses without increasing the predicted peak current ripple. These theoretical findings were further verified by simulations and experiments.

INDEX TERMS Z-source inverter, DC-link voltage, current ripple, switching frequency.

 NOMENCLATURE

\( d_s \) Shoot-through ratio
\( T_{sh} \) Total shoot-through time interval
\( f_s \) Switching frequency
\( V_{in} \) DC source voltage
\( V_{dc} \) DC-link voltage
\( T_0 \) Time interval of traditional zero vector
\( \Delta i \) Load current ripple
\( \Delta i_L \) Z-Source inductor current ripple
\( L \) The inductance of the load
\( L_z \) The inductance of the Z-source network

I. INTRODUCTION

The Z-Source inverter (Fig. 1) proposed by Zheng [1] is a power converter topology with significant advantages over other well-established systems. For example, the DC-link voltage of the network can be easily adjusted and it allows shoot-through states, thus increasing the system reliability [2]–[4].

By shifting between shoot-through and non-shoot-through states, capacitors and inductors are charged or discharged to boost the DC-link voltage. Since the ZSI was first proposed in 2003, new topologies, PWM strategies, and design parameters of Z-source networks have been extensively investigated [5]–[9]. However, the load current ripple of ZSIs has not been theoretically analyzed. Current ripple is an important issue in the design and control of inverters. For example, current ripple influences the torque ripple and the noise amplitude of inverters with a motor load. Current ripple is defined as the difference between instantaneous and fundamental current components, as shown in Fig. 2. Grandi et al. analyzed and compared peak current ripple within two-level and multilevel VSI [10] and derived the current ripple based on different sectors. Dong and Fei proposed a variable switching frequency PWM strategy for three-phase VSI [11], [12]. With this strategy, the current ripple can be predicted and controlled, thereby lowering the switching frequency and improving the EMI.

Unlike VSI, the ZSI has a unique shoot-through state in its working process. This shoot-through state influences the current ripple of ZSI. The switching control strategies for distributing the shoot-through state can be divided into two categories: SPWMs [13] and SVPWMs (SVMs) [14].
Compared to SPWMs, SVMs have many advantages such as higher voltage utilization, lower current harmonics and lower switching losses [15]. SVM6 and SVM4 are two typical control strategies. Both strategies can achieve the maximum shoot-through time which equals to the zero state time without additional switching actions and losses. According to SVM6, in one control cycle, the shoot-through time intervals are distributed to the three phase arms into six equal parts. Herein, the details of current ripple distribution based on SVM6 for ZSI are provided. The current ripple expression in each switching period is derived to predict the peak current ripple.

There are two schemes to regulate the DC-link voltage: constant voltage scheme and variable voltage scheme. In 2004, the Toyota Corporation applied a constant-voltage scheme, the Buck-Boost DC/DC converter, in the Prius hybrid drive system. The battery voltage was constantly boosted to 500 V to supply energy to the inverter without increasing the volume and weight of the system [16]. It broadened the output torque and the power of the motor system. Implementing a constant boost voltage system would improve the system efficiency [17], [18]. A variable DC-link voltage scheme was also used in drive systems [19], [20]. By controlling the DC-DC booster, the DC-link voltage could be set as the minimum system voltage to operate the machine. The permanent magnet synchronous motor drive system with the bidirectional Z-Source inverter was proposed for electric vehicles [21]–[23]. In this system, the reference DC-link voltage was calculated online with the motor speed and the lower DC-link voltage resulted in the smaller ripple current. Therefore, we adopted a variable DC-link voltage scheme to achieve a minimum DC-link voltage.

In order to obtain good current characteristics, the relatively high switching frequency of the inverters is generally set, thus increasing the switching loss. As for ZSIs, due to the adjustable DC-link voltage, it is possible to lower the DC-link voltage and the switching frequency under the condition of a low speed load. Based on a detailed analysis of ripple current for ZSIs, we chose a variable switching frequency method to reduce the switching loss without increasing the predicted peak current ripple.

II. ANALYSIS OF CURRENT RIPPLES FOR THE ZSI AND VSI

With reference to the DC-link mid-point \( n \) (Fig. 1), the three-phase load terminal voltage can be expressed as follows:

\[
\begin{align*}
    v_a &= \frac{V_{dc}}{2} (2d_a - 1) \\
    v_b &= \frac{V_{dc}}{2} (2d_b - 1) \\
    v_c &= \frac{V_{dc}}{2} (2d_c - 1),
\end{align*}
\]

where \( d_a, d_b \) and \( d_c \) are respectively the duty cycles of Phases A, B and C. Phase A is discussed below. When Phase A is in the shoot-though state, the Thevenin equivalent circuits are shown in Fig. 3 [11], [12]. Although the load freewheeling states are different, their equivalent circuits are the same.

When Phase B or Phase C is in the shoot-though state, Thevenin equivalent circuits are the same as the equivalent circuits with Phase A in the shoot-though state. When the ZSI is in the shoot-though state, the current slope of Phase A can be derived as Eq. (2). Combining Eq. (1) with Eq. (2), the current slope can be derived as Eq. (3).

\[
\begin{align*}
    \frac{di_a}{dt} &= \frac{2}{3L} \left( v_b + v_c - v_a \right) \\
    \frac{di_a}{dt} &= \frac{V_{dc}}{3L} (d_b + d_c - 2d_a)
\end{align*}
\]

Similarly, the basic eight-voltage vectors are applied in the converter when the ZSI is in the non-shoot-though state. Thevenin equivalent circuits can be also derived and the slope of the current ripple is summarized in Table 1 [11], [12].
TABLE 1. Calculated slope of the current ripple.

| State of ZSI | Voltage Vector | \( \frac{di_x}{dt} \) |
|--------------|----------------|---------------------|
| shoot-through state | \( V_{dc} \) \( (d_b + d_c - 2d_a) \) | \( \frac{V_{dc}}{3L} \) \( (d_b + d_c - 2d_a) \) |
| 000/111 | \( \frac{V_{dc}}{3L} \) \( (d_b + d_c - 1 - 2d_a) \) |
| non-shoot-through state | \( \frac{V_{dc}}{3L} \) \( (d_b + d_c - d_a) \) | \( \frac{V_{dc}}{3L} \) \( (d_b + d_c - d_a) \) |
| 011 | \( \frac{V_{dc}}{3L} (1 + d_b + d_c - d_a) \) |
| 100 | \( \frac{V_{dc}}{3L} (1 + d_b + d_c - d_a) \) |
| 101/110 | \( \frac{V_{dc}}{3L} (1 + d_b + d_c - d_a) \) |

FIGURE 4. DC-link voltage and current ripples of ZSI.

The DC-link voltage and current ripple waveform of ZSI in one switching period are shown in Fig. 4. The current ripples at the beginning and the end of a sampling period are the same and equal to zero. The SVM is symmetrical, so the waveform of current ripple is antisymmetric around the middle point of the sampling period \( T_s/2 \). The ripple current slopes for \( y_1 \), \( y_2 \) and \( y_3 \) are respectively \( k_1 \), \( k_2 \) and \( k_3 \) and the instantaneous current ripple \( y_x \) (\( x = 1, 2, 3 \)) (Fig. 4) can be calculated as follows:

\[
\begin{align*}
y_1 & = k_1 \cdot \left( \frac{T_0}{4} - \frac{T_{sh}}{12} \right) \\
y_2 & = y_1 + k_2 \cdot \frac{T_1}{2} \\
y_3 & = y_2 + k_3 \cdot \frac{T_{sh}}{6}.
\end{align*}
\]

The peak current ripple can be expressed as:

\[ \Delta i_{ZSI} = \max(y_1, y_2, y_3). \]  

FIGURE 5. Current ripples in one section of VSI.

The instantaneous current ripple \( y_x \) (\( x = 1, 2 \)) (Fig. 5) can be calculated as follows:

\[
\begin{align*}
y_1 & = k_1 \cdot \frac{T_0}{4} \\
y_2 & = y_1 + k_2 \cdot \frac{T_1}{2}
\end{align*}
\]

The peak current ripple can be expressed as:

\[ \Delta i_{VSI} = \max(y_1, y_2). \]  

III. VARIABLE DC-LINK VOLTAGE AND SWITCHING FREQUENCY TO CONTROL CURRENT RIPPLE

From TABLE 1, the ripple current slope is positively correlated with the DC-link voltage. The ripple current slope decreases when the DC-link voltage is reduced. If the DC-link voltage is adjustable, then the current ripple can be controlled.

The maximum shoot-through duty \( d_s \) of ZSI is restricted by the modulation factor \( m \):

\[ d_s \leq 1 - m. \]  

Under the same load condition, to achieve the minimum DC-link voltage, \( m \) should be maximized:

\[ m = 1 - d_s. \]  

The modulation factor and the DC-link voltage can be expressed as follows:

\[ m = \frac{\sqrt{3} |\vec{V}_{ref}|}{V_{dc}}, \]  

\[ V_{dc} = \frac{1}{1 - 2d_s} V_{in}. \]  

Combining Eqs. (9) and (10) with Eq. (11), the modulation factor is also derived as:

\[ m = \frac{\sqrt{3} |\vec{V}_{ref}|}{2\sqrt{3} |\vec{V}_{ref}| - V_{in}}. \]

The above analysis indicates that the current ripple is related to the phase angle \( \theta \) of reference vector with SVM control. Under the condition that the duty cycles of the three phases are obtained, the peak current ripple can be predicted. When the peak current ripple is set as the control target, the prediction switching frequency is:

\[ f_s = f_N \times \frac{\Delta i^*}{\Delta i}, \]
where \( \Delta i^* \) is the expected current ripple; \( \Delta i \) is the reference current ripple; \( f_s \) is the prediction switching frequency; \( f_N \) is the reference switching frequency.

The adjustable switching frequency strategy can reduce the switching loss. However, it may increase the ZSI network inductor current ripple. The inductor current ripple can be expressed as follows [24]:

\[
\Delta i_L = \frac{md_V}{4Ld_s(1-2d_s)}.
\]

To ensure that the inductor current ripple meets the design requirements, the minimum switching frequency should be:

\[
f_{s \text{ min}} = \frac{m_{\text{max}}d_{\text{max}}V_{\text{in}}}{4L(1-2d_{\text{max}})\Delta i_{L \text{ max}}},
\]

where \( \Delta L_{\text{max}} \), \( m_{\text{max}} \), and \( d_{\text{max}} \) are respectively the maximum of inductor current ripple, modulation factor and shoot-through duty. When \( f_s \leq f_{s \text{ min}} \), \( f_{s \text{ min}} \) is set to be the switching frequency, otherwise \( f_s \) is chosen as the switching frequency.

The proposed adjustable DC-link voltage and switching frequency strategy is shown in Fig. 6.

**IV. COMPARISONS OF CURRENT RIPPLES WITH DIFFERENT SCHEMES**

To illustrate the current ripples of different converters, a ZSI and a VSI are respectively designed according to the following parameters: ZSI: DC-source voltage \( V_{\text{in}} = 65 \text{ V} \); Z-source network: inductor \( L_z = 1 \text{ mH} \); capacitor \( C = 550 \mu \text{F} \); shoot-through duty \( d_s = 0.25 \); the DC-link voltage is calculated to be \( V_{dc} = 130 \text{ V} \); VSI: DC-source voltage \( V_{\text{in}} = 130 \text{ V} \).

Both the ZSI and VSI are working under the following conditions: the same three-phase load resistance \( R = 20 \Omega \); inductance \( L = 1.15 \text{ mH} \); switching frequency \( f_s = 5 \text{ kHz} \); the modulation index \( m = 0.69 \).

**A. COMPARISONS OF PEAK CURRENT RIPPLE**

The predicted theoretical current ripple waveforms of the ZSI and VSI are shown in Fig. 7. In most angle intervals, compared to the ZSI, the VSI results in the lower current ripples. However, in other intervals, the results are opposite. When the angle is 0\(^\circ\) or 180\(^\circ\), the current ripple of the ZSI reaches its maximum 1.1A, which is 0.2A higher than that of the VSI. The peak current ripple of the ZSI is equal to that of the VSI at 60\(^\circ\)-120\(^\circ\) and 240\(^\circ\)-300\(^\circ\) intervals. The maximum current ripple value is 1.3A.

**B. COMPARISONS OF CURRENT RIPPLE RMS VALUE**

The current ripple RMS value of the ZSI could be derived from Fig. 4. The RMS value of current ripple in 0-t1 interval is

\[
\frac{4}{T_s} \int_0^{T_0/4} \left( \frac{y_1}{T_0/4-T_{sh}/12} \right)^2 dt = \frac{y_1^2}{3}
\]

Similarly, the RMS value of current ripple in t1-t2 interval is \((y_1^2 + y_1y_2 + y_2^2)/3\); the RMS value of current ripple in t2-t3 interval is \((y_2^2 + y_1y_2 + y_2^2)/3\); the RMS value of current ripple in t3-t4 interval is \((y_3^2 - y_3y_4 + y_4^2)/3\); Combining these expressions with non-shoot-through time and shoot-through time, the current ripple RMS value of the ZSI in the whole switching cycle can be shown in (16).

\[
\Delta_{\text{r-ZSI}} = \sqrt{\frac{1}{3T_s} \left( T_0 - T_0^d \right) \cdot \frac{y_1^2 + T_1 \cdot (y_1^2 + y_1y_2 + y_2^2)}{y_1^2 - y_2y_3 + y_3^2} + T_2 \cdot \frac{(y_3^2 - y_3y_4 + y_4^2)}{y_2^2 - y_2y_3 + y_3^2} \right)}
\]

where \( y_1 < 0, y_2 > 0, y_3 > 0 \) and \( y_4 = -y_1 \).

Similarly, by Fig. 5, the current ripple RMS value of the VSI in the whole switching cycle can be shown in (17).

\[
\Delta_{\text{r-VSI}} = \sqrt{\frac{1}{3T_s} \left( T_0 \cdot y_1^2 + T_1 \cdot (y_1^2 + y_1y_2 + y_2^2) + T_2 \cdot (y_2^2 - y_2y_3 + y_3^2) \right)}
\]
Fig. 9 shows the comparison the current ripple RMS value (calculated by (16) and (17)) of the ZSI and VSI with different angle in the first section. From Fig. 9, one can get that the ZSI generates bigger current ripple RMS value than that of the VSI. In the worst case, current ripple RMS value of the ZSI is about 0.45A, which is 50% higher than that of the VSI.

C. COMPARISONS OF CURRENT RIPPLE WITH VARIABLE AND CONSTANT VOLTAGE SCHEMES

Fig. 9 shows the current ripple comparison of the variable DC-link voltage and the constant voltage schemes with the input voltage of 75 V. In the first voltage regulation scheme, the DC-link voltage is kept at a constant value (150 V) with \( d_s = 0.25 \), as indicated in blue lines. In the second voltage regulation scheme, the adjustable DC-link voltage strategy is adopted according to the load conditions, as indicated in red lines.

In Fig. 9, when the DC-link voltage is a constant 150V and the modulation index is set to be 0.55, 0.60, 0.70 and 0.73, the peak current ripple is 1.2A, 1.3A, 1.5A and 1.6A, respectively. The larger the modulation index is, the larger the current ripple will be. When the variable DC-link voltage is 89.5V, 104V, 134V and 144V, the current ripple difference between the two voltage regulation schemes is about 0.6A, 0.5A, 0.2A and 0.1A, respectively. We can get that current ripple in the second scheme is lower than that in the first scheme. Especially with the low reference voltage, the advantage of the variable DC-link scheme is more obvious. The maximum peak current ripple of the constant voltage scheme is about 175% higher than that of the variable DC-link voltage scheme, as shown in Fig. 9(a).

D. COMPARISONS OF OUTPUT WAVEFORM QUALITY

Fig. 10 shows the FFT analysis of load current of the ZSI and VSI. As shown in Fig. 10, the 5th harmonic is dominant in the harmonics. The total harmonic distortion (THD) of the ZSI (23.75%) is slightly worse than that of the VSI (23.28%).

V. EXPERIMENTAL RESULTS

To verify the variable DC-link voltage and switching frequency strategy, a ZSI was designed with the DC-source voltage \( V_{in} = 100 \) V and the switching frequency range: \( f_s = 7.5 \sim 10 \) kHz. For ZSI network design, the inductance and capacitance are determined with following equations [24]:

\[
L_c \geq \frac{m d_s V_{in}}{4 k I_L f_s (1 - d_s)},
\]

(18)
where $\Delta i_L$ is the inductor current ripple; $k_i$ is the current ripple coefficient; $\Delta V_c$ is the capacitor voltage ripple; $k_c$ is the voltage ripple coefficient.

Under the settings: maximum shoot-through ratio $d_s = 0.25$, the switching frequency $f_s = 10$ kHz and the current ripple coefficient $k_i = 20\%$, we could get $L_c \geq 0.76$ mH. Under the voltage ripple coefficient $k_c = 10\%$, we could get $C \geq 13$ µF. Finally, we chose the ZSI network inductor $L_1 = L_2 = 1$ mH, network capacitor $C_1 = C_2 = 100$ µF. The Infineon half-bridge module BSM60GB was used to form the inverter bridge. STTH60RQ06W ultrafast recovery diodes were employed as the switches. Concept-2SC0108T driver boards were used to trigger IGBTs. To reduce the equivalent series resistance (ESR), we adopted a film capacitor. Parameters of the ZSI used for experiments are shown in Table 2. The photo of the ZSI experimental platform is shown in Fig. 11.

In the modulation, the strategy of SVM is adopted, as shown in Fig. 12. For the SVM, the shoot-through states are inserted at the beginning or the end of switching moment. The switches are turned on in advance or turned off with delay without increasing the switching frequency. In Fig. 11, $T_a$, $T_b$ and $T_c$ are the same to those of the traditional SVPWM and respectively denote the a-, b- and c-phase switching times for the bridge arms. The subscripts of “+” and “−” are used to distinguish the switching times of the upper and lower arm switches. For example, $T_{a+}$ is the conduction time of phase a upper switch. In a control cycle, the total shoot-through state is divided into six equal parts and added into the traditional zero-state vector.

The switching times are expressed as [26]:

$$
\begin{align*}
T_{a+} &= T_a + \frac{T_{sh}}{12} \\
T_{a-} &= T_a + \frac{T_{sh}}{4} \\
T_{b+} &= T_b - \frac{T_{sh}}{12} \\
T_{b-} &= T_b + \frac{T_{sh}}{12}
\end{align*}
$$
FIGURE 13. IGBTs driver signal generation logic circuit.

\[
V_{\text{ref}} \left( \frac{9}{(11)} \right) \xrightarrow{d_a \cdot d_b \cdot d_c} V_{\text{dc}} \xrightarrow{\text{Tab 1}} k_1 \kappa_2 \kappa_3 \xrightarrow{T_k} \begin{cases} T_{c^+} = T_c - \frac{T_{sh}}{4} \\ T_c = T_c - \frac{T_{sh}}{12}. \end{cases} \]  

(20)

where \( T_{sh} \) indicates the total shoot-through time, \( T_{sh} = d_c \cdot T_0 \).

By changing the shoot-through ratio, various shoot-through times can be realized.

During the experiments, TMS320F2812 was used to generate the PWM signals. The built-in event manager modules of DSP (EVA and EVB) can automatically generate SVPWM signals. IGBTs driver signal generation logic circuit is shown in Fig. 13.

Fig. 14 shows the diagram of the algorithm executed in TMS320F2812. As we all know, TMS320F2812 is a digital signal processor (DSP). It has a hardware multiplier, which is extremely fast and can implement various processing algorithms in real time. The DSP can complete a multiplication and accumulation operation in one clock cycle. For the division operation, the IQmath library can be used, and its operation time is about one clock cycle \( T_{\text{clock}} \).

Table 3 lists the time taken by the variable DC-link voltage and switching frequency algorithm. As can be seen from Table 3, the system needs 28 \( T_{\text{clock}} \) to execute the algorithm. If the DSP clock frequency is 150 MHz, it takes about \( T_{m} = 187 \text{ ns} \) to execute the algorithm. When the converter switching frequency \( f_s = 10 \text{ kHz} \), the switching period \( T_s = 100 \mu \text{s} \). We can see that \( T_m = 0.00187 \text{ ns} \ll T_s \). The computational burden introduced by the algorithm is trivial, and the DSP can perform real-time calculations.

Figs. 15(a)-15(b) show the simulation results of ZSI and VSI, respectively. The shoot-through ratio \( d_s \) is set to 0.25. In all the figures, the simulation results (blue traces) and the prediction ripple envelopes (red traces) are shown together. It is worth noting that the equations (4)-(7) predict the peak current ripple. The predicted peak-peak current ripple is positive and negative symmetrical. The important parameter is the current ripple amplitude. As shown in Fig. 14, when the simulation result is 1.15A, the theoretical prediction is 1.2A. The prediction accuracy is about within 5%. The simulation results are well consistent with the predictions obtained with the theory introduced above.

A CP8030H with 100-MHz bandwidth current probe was employed to obtain the load current. After measuring the load current, the measured data were fed to Matlab to calculate its ripples.

Figs. 16(a) and 16(b) show the load current and ripple, respectively. As shown in Fig. 16(b), the experimental peak current ripple is about 0.8 A, which is equal to the prediction value which is calculated by (4)-(5).

If the predicted peak current ripple was set to be 1.1 A, then we could lower the DC-link voltage and switching frequency by the strategy (Fig. 6). According to Fig. 6, the switching frequency could be lowered to 7.5 kHz. When the DC-link voltage was set to be the minimum system voltage for the
load operating point, the parameters were changed as follows: shoot-through duty $d_s = 0.08$; DC-link voltage $V_{dc} = 122$ V; the modulation factor $m = 0.9$. The experimental results are shown in Fig. 17.

Although the DC-link voltages were different, the load currents were the same (Fig. 16 and Fig. 17), indicating that the two schemes were working under the same load conditions. Fig. 17(b) shows the current ripple with the maximum value 1.08 A, which is lower than the expected value 1.1 A. The improvement for the converter is that the switching frequency was reduced 25%, which is helpful to reduce the IGBTs switching loss. The computational burden introduced by the algorithm is trivial, and the controller can perform real-time calculations.

**FIGURE 16.** Constant DC-link voltage scheme: (a) DC-link voltage and load current in line period, (b) current ripple, (c) DC-link voltage and the inductor current in carrier period.

**FIGURE 17.** Adjustable DC-link scheme: (a) DC-link voltage and the load current in line period, (b) current ripple, (c) DC-link voltage and the inductor current in carrier period.
VI. DISCUSSION
The ZSI converts partial or all of the traditional zero states into the shoot-through states to achieve the purpose of adjusting the DC-link voltage. The different positions of the shoot-through vector distribution have different effects on the current ripple. The positions of the shoot-through vector affect the RMS of current ripple other than the peak current ripple. The slopes of current ripples in the shoot-through state and traditional zero state are the same (TABLE 1). According to SVM4 [25], the total shoot-through time interval is only inserted in the traditional zero state. Therefore, if the ZSI and VSI are working with the same $V_{dc}$ and $m$, the current ripple will be equal to that of VSI when SVM4 is applied in ZSI. However, if the ZSI is working with SVM6 strategy, the load current ripple will be different from that of VSI.

VII. CONCLUSION
The current ripple for ZSI is analyzed in the paper. Compared to VSI, ZSI results in the higher current ripples in most angle intervals. The peak current ripple of ZSI is equal to that of VSI. Under certain conditions, the THD of the ZSI (23.75%) is slightly worse than that of the VSI (23.28%). According to the adjustable DC-link voltage and switching frequency strategy, the switching frequency can be reduced 25%. The simulation and experimental results verified the proposed analysis and control approach. The predicted current ripples accuracy is about within 5%.

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