A New Z-Source Inverter Topology with High Voltage Boost Ability

Quoc-Nam Trinh* and Hong-Hee Lee†

Abstract – A new Z-source inverter (ZSI) topology is developed to improve voltage boost ability. The proposed topology is modified from the switched inductor topology by adding some more inductors and diodes into inductor branch to the conventional Z-source network. The modulation methods developed for the conventional ZSI can be easily utilized in the proposed ZSI. The proposed ZSI has an ability to obtain a higher voltage boost ratio compared with the conventional ZSI under the same shoot-through duty ratio. Since a smaller shoot-through duty ratio is required for high voltage boost, the proposed ZSI is able to reduce the voltage stress on Z-source capacitor and inverter-bridge. Theoretical analysis and operating principle of the proposed topology are explicitly described. In addition, the design guideline of the proposed Z-source network as well as the PWM control method to achieve the desired voltage boost factor is also analyzed in detail. The improved performances are validated by both simulation and experiment.

Keywords: Z-source inverter (ZSI), Voltage boost ability, DC-AC converter

1. Introduction

The voltage source inverters (VSI) are widely utilized in various applications such as variable speed motor drives and distributed generation systems [1]. However, the traditional VSI has inherent shortcomings such as the limitation of ac output voltage, the short circuit problem occurred by miss-gating from electromagnetic interference (EMI), and ac output distortion due to the existence of dead-time in pulse width modulation (PWM). The Z-source inverter (ZSI) is introduced as a competitive topology to overcome the shortcomings of the traditional VSI [3]. In these days, the ZSI is well known because of its outstanding characteristic, i.e., single stage buck-boost converter that can increase system efficiency and reduce system costs [4]. In order to employ the voltage boost ability in the ZSI, both switches in the same inverter phase leg turn “ON” simultaneously (shoot-through state). Because the shoot-through state is allowed in PWM, the reliability of the ZSI system is significantly increased and the ac output distortion is greatly reduced. Owing to these advantages, the ZSI topology is developed continuously and utilized successfully in various applications such as motor drives, fuel cell, PV, and wind power systems [5-10].

The conventional ZSI has two independent control variables, i.e., the shoot-through duty ratio \(D_s\) and the modulation index \(M\). The voltage boost of the ZSI is achieved by increasing the shoot-through duty ratio, while the ac output voltage is regulated according to the modulation index. However, there is a compromise between the shoot-through duty ratio and the modulation index: if a large modulation index is used, only a small shoot-through duty ratio can be utilized and vice-versa. In order to provide a strong boost factor in the conventional ZSI, a large shoot-through duty ratio is usually demanded to increase the inverter-bridge voltage from a low voltage dc source. Since a large shoot-through duty ratio is used, only a small modulation index is available to be utilized. Unfortunately, a small modulation index not only reduces amplitude of the ac output voltage but also degrades ac output performance [2]. Furthermore, a high voltage stress is imposed on Z-source capacitor and inverter-bridge when a large shoot-through duty ratio is applied. Therefore, the conventional ZSI has limitation on providing both a high boost factor \(B\) and a high output voltage simultaneously. In order to overcome these problems, several PWM methods have been developed [11, 12]. However, the improvement of the voltage boost ability in these methods is not sufficient to get high output voltage gain, also the voltage stress on Z-source capacitors and inverter-bridge are still high. Moreover, low-frequency ripple exists on the capacitor voltage [11]. Other novelties of the ZSI are achieved by changing the impedance network structure named quasi-ZSI [13]. These topologies have some advantages such as reducing the voltage stress on the Z-source capacitors as well as maintaining the continuous input current, but there is no improvement on voltage boost ability compared with the conventional ZSI.

Recently, researchers have focused on extending the Z-source network structure to increase the voltage boost ability. In [14], the high voltage boost ratio is achieved by adding one or more impedance stage such as one inductor, two diodes and one capacitor into the quasi-ZSI. In [15], the extended voltage boost ratio is obtained by combining
the concept of the switched inductor which is originally developed for DC/DC converter in [16] with the conventional ZSI. Even though those topologies are improved with respect to the voltage boost ability compared with conventional ZSI, the voltage stress on the Z-source capacitors and the inverter-bridge are still high under a high ac output voltage.

In this paper, by integrating a modified switched inductor topology that adds one inductor and three diodes into the traditional switched inductor structure with the conventional Z-source network, we introduce a new topology that is able to obtain higher boost ratio compared to that of the conventional ZSI including the topologies introduced in [14] and [15] by using the same shoot-through duty ratio. The voltage stress on Z-source capacitors and inverter-bridge is greatly reduced since a short shoot-through duty ratio can produce very high voltage boost. Theoretical analysis for the proposed topology is investigated and the results are compared with those of the conventional ZSI. In addition, the design criteria for passive components of the proposed ZSI topology as well as the PWM control method to realize the voltage boost ability is also presented in this paper. The improved performance is validated by both simulated and experimental results.

2. The conventional Z-source inverter

Fig. 1 shows a configuration of the conventional ZSI. As described in [3], the peak inverter-bridge voltage can be expressed as

\[ \hat{v}_i = BV_{dc} = \frac{1}{1 - 2D_0} V_{dc} \] (1)

where, \( V_{dc} \) is the dc input voltage, \( B \) is the voltage boost factor that is determined by \( D_0 \). The Z-source capacitor voltage is determined by

\[ V_C = \frac{1 - D_0}{1 - 2D_0} V_{dc} \] (2)

The peak phase ac output voltage can be expressed as

\[ \hat{v}_{ac} = M \frac{\hat{v}_i}{2} = \frac{MB}{2} V_{dc} \] (3)

where, \( M \) is the modulation index and \( \hat{v}_{ac} \) is the peak value of the ac output phase voltage. The voltage gain is defined as

\[ G = MB = \frac{\hat{v}_{ac}}{V_{dc}/2} \] (4)

Fig. 2 shows voltage gain versus the shoot-through duty ratio of the conventional ZSI. From Fig. 2, it can be seen that a high voltage gain can be obtained by increasing the shoot-through duty ratio close to the upper bound, i.e., 0.5. However, a high voltage gain results in a very high voltage stress on the Z-source capacitor and the inverter-bridge as shown in Fig. 3.

3. The proposed Z-source inverter

In order to reduce the voltage stress on the Z-source capacitor and inverter-bridge in case of high output voltage
demand, we propose a new Z-source inverter topology as shown in Fig. 4. As compared with the conventional ZSI structure shown in Fig. 1, the basic X shape structure of impedance circuit is maintained except that four inductors and twelve diodes are added. In Fig. 4, each group of components, i.e., \( L_1-L_2-L_3-D_1-D_2-D_3-D_4-D_5 \) in the upper branch or \( L_7-L_8-L_9-D_7-D_8-D_9-D_{10}-D_{11}-D_{12} \) in the lower branch of Z-source network replaces each single inductor in the conventional Z-source network. Owing to the combination of these components, the proposed topology is able to store and transfer a higher energy from the dc source to the inverter part compared with the conventional Z-source network.

Firstly, consider the shoot-through state that is represented by the closed switch. During this state, \( D_{in} \) is blocked. In the upper branch of Z-source network, four diodes \( D_1, D_2, D_3, \) and \( D_4 \) are conducted, while two diodes \( D_5 \) and \( D_6 \) are blocked. Three inductors \( L_1, L_2, \) and \( L_3 \) are connected in parallel and charged by capacitor \( C_1. \) Similarly for the lower branch, four diodes \( D_7, D_8, D_9, \) and \( D_{10} \) are conducted, while two diodes \( D_{11} \) and \( D_{12} \) are blocked. Three inductors \( L_4, L_5, \) and \( L_6 \) are connected in parallel and charged by capacitor \( C_2. \) The equivalent circuit is shown in Fig. 6(a).

The equivalent circuit of the non-shoot-through state (include active and null state) is shown in Fig. 6(b), where the switch \( S \) is opened. During this state, \( D_{in} \) is conducted. In the upper branch, four diodes \( D_1, D_2, D_3, \) and \( D_4 \) are blocked, while two diodes \( D_5 \) and \( D_6 \) are conducted. Three inductors \( L_1, L_2, \) and \( L_3 \) are connected in series and the stored energy is transferred to inverter circuit. Likewise, in lower branch, four diodes \( D_7, D_8, D_9, \) and \( D_{10} \) are blocked, while two diodes \( D_{11} \) and \( D_{12} \) are conducted. Three inductors \( L_4, L_5, \) and \( L_6 \) are connected in series and the stored energy is transferred to inverter circuit.

3.1 Equivalent circuit and operation principles

The operation principles of the proposed impedance network are similar to those of the conventional Z-source network, which is classified into two states: shoot-through state and non-shoot-through state. For the sake of simplification, Fig. 5 shows the equivalent circuit of the proposed topology viewed from the inverter-bridge side, where the three phase inverter bridge is replaced with a current source and a single switch \( S \).

![Fig. 4. Topology of the proposed Z-source inverter](image1)

![Fig. 5. Equivalent circuit of the proposed Z-source inverter](image2)

![Fig. 6. Equivalent circuit of Fig. 4: (a) shoot-through state; (b) non shoot-through state](image3)
3.2 Analysis of the new Z-source network and voltage boost ability

Assuming that the six inductors \((L_1-L_6)\) have the same inductance \((L)\) and two capacitors \((C_1\) and \(C_2)\) have the same capacitance \((C)\). As a result, the network becomes symmetrical. From symmetrical circuit, the voltage across capacitors and inductors become

\[
\begin{align*}
V_{C_1} &= V_{C_2} = V_C \\
v_{1} &= v_{12} = v_{13} = v_{14} = v_{15} = v_{16} = v_L
\end{align*}
\]

(5)

From Fig. 6(a), voltage equations in the shoot-through state are derived as follows:

\[
\begin{align*}
v_L &= V_C \\
v_s &= 0
\end{align*}
\]

(6)

Now, consider the non-shoot-through state. From Fig. 6(b), the voltage equations can be obtained as follows:

\[
\begin{align*}
3v_L &= V_{dc} - V_C \\
v_s &= V_C - 3v_L = 2V_C - V_{dc}
\end{align*}
\]

(7)

From the fact that the average voltage of the inductors over one switching period \(T\) should be zero in steady state, (8) can be derived by using (6) and (7):

\[
V_L = \frac{T_0 V_C + (T - T_0) \frac{V_{dc} - V_C}{3}}{T} = 0
\]

(8)

From (8),

\[
V_C = \frac{1 - D_0}{1 - 4D_0} V_{dc}
\]

(9)

The peak dc-link voltage across the inverter bridge is expressed in (7) and can be rewritten:

\[
\dot{v}_1 = V_C - 3v_L = 2V_C - V_{dc} = \frac{1 + 2D_0}{1 - 4D_0} V_{dc}
\]

(10)

Thus, the voltage boost factor \(B\) is expressed as

\[
B = \frac{1 + 2D_0}{1 - 4D_0}
\]

(11)

Fig. 7 shows the boost factor \(B\) versus the shoot-through duty ratio \(D_0\) obtained from (1) and (11) in order to compare the voltage boost ability of the proposed ZSI with that of the conventional one. From Fig. 7, it is obvious that the voltage boost ability of the proposed ZSI is increased significantly. A short shoot-through duty ratio is enough to provide a high voltage boost ratio.

![Fig. 7. Voltage boost ability of the proposed ZSI and the conventional ZSI](image)

3.3 Analysis of voltage gain ability and voltage stress

From (4), it can be seen that the voltage gain \(G\) of the ZSI is the combination of the voltage boost factor \(B\) of Z-source network and the modulation index \(M\). Due to the compromise between \(D_0\) and \(M\), the voltage gain is varied according to the boost factor and PWM control method. In this paper, the simple boost control method is utilized to determine the whole voltage gain ability of the proposed ZSI and the result is compared with that of the conventional one.

![Fig. 8. PWM waveform of simple boost control method](image)
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\[ G_{\text{max}} = MB = (1 - D_0) \frac{1 + 2D_0}{1 - 4D_0} \]  \hspace{1cm} (12)

Similarly, the maximum voltage gain of the conventional ZSI is defined as

\[ G_{\text{max}} = MB = (1 - D_0) \frac{1}{1 - 2D_0} \]  \hspace{1cm} (13)

Fig. 9 shows the voltage gain \( G_{\text{max}} \) versus the shoot-through duty ratio \( D_0 \) of the proposed ZSI and the conventional ZSI obtained from (12) and (13), respectively. In Fig. 9, it is obvious that the maximum voltage gain of the proposed ZSI is much higher than that of the conventional ZSI under the same shoot-through duty ratio \( D_0 \). It means that a shorter shoot-through duty ratio is used in the proposed ZSI to generate the same ac output voltage.

Assuming that both the proposed ZSI and the conventional ZSI work under the same voltage gain \( G \) from (12), the required shoot-through duty ratio is obtained as

\[ D_0 = \frac{(4G + 1) - \sqrt{16G^2 + 9}}{4} \]  \hspace{1cm} (14)

Substituting (14) into (9) and (11), the voltage stress on Z-source capacitor and inverter-bridge of the proposed ZSI, respectively, are calculated as

\[ V_c = \frac{\sqrt{16G^2 + 9} - (4G - 3)}{4(\sqrt{16G^2 + 9} - 4G)} V_{dc} \]  \hspace{1cm} (15)

\[ \hat{v}_i = \frac{(4G + 3) - \sqrt{16G^2 + 9}}{2(\sqrt{16G^2 + 9} - 4G)} V_{dc} \]  \hspace{1cm} (16)

Substituting (17) into (1) and (2), similarly, the voltage stress on Z-source capacitor and inverter-bridge of the conventional ZSI, respectively, are determined as

\[ V_c = G V_{dc} \]  \hspace{1cm} (18)

\[ \hat{v}_i = (2G - 1) V_{dc} \]  \hspace{1cm} (19)

Fig. 10 shows the comparison of voltage stress between the proposed ZSI and the conventional ZSI. As shown in Fig. 10, under the same voltage gain \( G \), the voltage stress on the Z-source capacitor and the inverter-bridge of the proposed ZSI are much lower than those of the conventional ZSI.

![Fig. 9. Voltage gain of the proposed ZSI and the conventional ZSI](image)

For the conventional ZSI, from (13), the required shoot-through duty ratio is defined as

\[ D_0 = \frac{G - 1}{2G - 1} \]  \hspace{1cm} (17)

![Fig. 10. Voltage stress comparison between the proposed ZSI and the conventional ZSI](image)
3.4 Design criteria for the proposed Z-source network

Due to a tradeoff between output performance and system cost, selection of a reasonable value for passive components in Z-source network is an essential, especially for the proposed topology, because it uses more passive components than the conventional one.

The basic design guideline of the conventional ZSI is given in [17, 18]. Following that design procedure, the critical condition for selecting the passive components of the proposed ZSI can be found.

The size of inductors is determined by the inductance and the current level. The average current through the inductor \( I_L \) is determined by the output power \( P_{out} \) and the input dc voltage \( V_{dc} \)

\[
I_L = \frac{P_{out}}{V_{dc}} \tag{20}
\]

From (6), the voltage across the inductors in shoot-through state is defined as \( V_C \). Therefore, the current ripple in the inductor is defined by

\[
\Delta I_L = \frac{V_C DLT}{L} \tag{21}
\]

From (21), the inductance can be chosen according to the required current ripple through inductor. It is usual to select the inductance as small as possible to reduce weight, volume, and system cost. On the other hand, it must be high enough to prevent undesired operation modes, which is explicitly described in [19]. As explained in [19], under the new operation modes, the voltage on inverter-bridge is no longer constant during the non-shoot-through states. Consequently, it will increase distortion in ac output voltage and degrade the output performance. In order to avoid unexpected operation modes, the minimum inductor current must be higher than the half of the peak current to the inverter-bridge \( i_1 \).

\[
I_{L,\text{min}} = \frac{P_{out}}{V_{dc}} - \frac{V_C DLT}{2L} \geq \frac{i_1}{2} \tag{22}
\]

Assuming that the proposed system works with a load impedance \( Z \) with power factor \( \cos \phi \), the output power can be expressed as

\[
P_{out} = \frac{3}{2} \frac{\bar{v}^2}{Z} \cos \phi = \frac{3}{2} \frac{\cos \phi V_{dc}^2}{Z} \left(1 - D_b\right) \left(\frac{1 + 2D_b}{1 - 4D_b}\right)^2 \tag{23}
\]

The peak inverter-bridge current is defined as

\[
i_1 = \frac{\bar{v}}{Z} - \frac{V_{dc}}{Z} \left(1 - D_b\right) \left(\frac{1 + 2D_b}{1 - 4D_b}\right) \tag{24}
\]

Substituting (9), (23), and (24) into (22), the required inductance is determined as

\[
L \geq \frac{(1 - D_b) D_b T}{2Z} \left(\frac{1 - D_b}{1 + 2D_b}\right)^2 - \frac{(1 + 2D_b)}{2Z} \tag{25}
\]

The inductor current increases in shoot-through states and reduces in non-shoot-through state. Therefore, the minimum inductor current occurs in non-shoot-through state. In this state, the inductors are connected in series, thus the required inductance of each single inductor is one third of the required value defined in (25).

For the conventional ZSI, similarly, the required inductance to avoid the unexpected operation modes is defined as

\[
L \geq \frac{D_b T}{2Z} \left(\frac{1 - D_b}{1 - 2D_b}\right) - \frac{1}{2Z} \tag{26}
\]

In order to compare the required inductance of the proposed ZSI with the conventional one, let’s assume that both systems work under the same condition in the input voltage, voltage boost factor, and load impedance.

![Normalized Required Inductance](image)

Fig. 11. Normalized required inductance for the proposed ZSI

Fig. 11 shows the normalized required inductance for each single inductor of the proposed ZSI which is the ratio between required inductance obtained from (25) and that obtained from (26). From Fig. 11, it can be seen that the required inductance for each single inductor is lower than one third of those in the conventional one. Therefore, total inductance of three inductors in the proposed ZSI is equal to or less than one inductor in the conventional ZSI. Consequently, even though the proposed ZSI needs more inductors than the conventional one, we can say that the volume of the proposed system is almost the same as that of conventional one.
4. Simulation and experimental results

In order to verify the improved voltage boost ability of the proposed topology, several simulations and experiments are carried out with the following parameters:

1. DC input voltage $V_{dc}=50V$
2. Z-source network: $L_1 = L_2 = L_3 = L_4 = L_5 = L_6 = 300\mu\text{H}, C_1 = C_2 = 470\mu\text{F}$
3. Three phase output filter $L_f = 1.2\text{mH}, C_f = 22.5\mu\text{F}$
4. Three phase resistive load $R = 15\Omega$
5. Switching frequency $f_s = 10\text{kHz}$

The simulations are performed by using PSIM software. The proposed ZSI is compared to the conventional ZSI under the same shoot-through duty ratio (case 1) and the same output voltage (case 2).

Case 1: the proposed system works with shoot-through duty ratio, $D_0=0.2$ and modulation ratio, $M=0.8$. In this case, the boost factor, $B=7$, voltage gain, $G=5.6$, the Z-source capacitor voltage, $V_C=200\text{V}$, the inverter-bridge voltage, $V_i=350\text{V}$, and the peak phase-to-phase output voltage, $v_{ab}=220\text{V}$. Fig. 12(a) shows the simulated results of the proposed ZSI, where Z-source capacitor voltage, input DC voltage, inverter bridge voltage and phase-to-phase output voltage are plotted, respectively.

However, the voltage boost and the voltage gain ability are significantly decreased when the same values of $D_0$ and $M$ are applied to the conventional ZSI. It can be seen clearly in Fig. 12(b): only 83V peak inverter-bridge voltage and 55V phase-to-phase output voltage can be obtained at the AC side, which is much lower than the peak inverter-bridge voltage 350V, and the phase-to-phase output voltage, 220V, achieved by the proposed ZSI.

Case 2: the proposed system works to obtain 200V phase-to-phase output voltage at AC side. By theoretical analysis, the shoot-through duty ratio and modulation index become $D_0=0.19$ and $M=0.81$, respectively. Corresponding voltages at capacitor and the inverter bridge are $V_C=175\text{V}, V_i=300\text{V}$, respectively. Fig. 13(a) shows the simulated results for the proposed ZSI.

For the case of the conventional ZSI, in order to obtain the same phase-to-phase output voltage, 200V, a very large shoot-through duty ratio is needed: the corresponding shoot-through duty ratio and modulation index are $D_0=0.44$, 

![Fig. 12. Simulation results in case 1](image1)

![Fig. 13. Simulation results in case 2](image2)
$M = 0.56$, respectively. From Fig. 13(b), the capacitor voltage $V_C$ is 250V and the inverter bridge voltage $v_i$ is 450V. It is apparent that the voltage stress on inverter-bridge and capacitors are significantly increased if we compare these values with those in Fig. 13(a).

An experiment system is built in laboratory with the same parameters used in simulation. The PWM control signal with a shoot-through state is generated by a high performance DSP TMS320F28335 from Texas Instruments. Fig. 14 shows the experimental results in case 1 for the proposed ZSI and the conventional ZSI. In Fig. 14(a), the Z-source capacitor voltage is 190V, the inverter-bridge voltage is 330V, and the peak phase-to-phase output voltage is 210V, which are much higher than those of the conventional ZSI shown in Fig. 14(b), i.e., 67V on the Z-source capacitor voltage, 83V on the inverter-bridge voltage, and 55V on the phase-to-phase output voltage. Fig. 15 shows the experimental results of both systems in case 2. From Fig. 15(b), the voltage stress on the Z-source capacitor of the conventional ZSI is 240V and the inverter bridge is 430V, which are much higher than those of the proposed ZSI shown in Fig. 15(a), i.e., 170V and 280V, respectively. In experimental results, there are some voltage spikes at inverter-bridge and capacitor voltage ($v_i$ and $V_C$) which do not exist in the simulation results. These ripples are caused by the stray inductance due to the connecting wires which are used to connect Z-source components in the experimental system. If the stray inductance is minimized properly, the ripple can be reduced.

In addition, as compared with the simulated results, there is small reduction on the voltage boost factor in experimental results due to effect of parasitic resistance on inductors.

The experimental results agree with the theoretical analysis and simulation study very well.

**5. Conclusions**

This paper has proposed a new ZSI topology to increase the voltage boost ability by adding some more inductors and diodes into the conventional Z-source network. Furthermore, this paper provides the effective boost control method and the design criteria for the new ZSI topology. The proposed ZSI is analyzed theoretically and the improved performances are compared with those of the conventional ZSI. The proposed topology has a higher voltage boost ratio and a lower voltage stress across the Z-
source capacitors and the inverter-bridge compared to the conventional topology under the same output voltage magnitude. The improved performance of the proposed ZSI is validated by both simulation and experimental results.

Even though the proposed ZSI needs more inductors and diodes than the conventional one, total inductance used in the proposed ZSI is equal to or lower than that of one inductor in the conventional ZSI. Thus, volume and cost of the proposed system are almost same as those of the conventional one. Thanks to the merit of voltage boost improvement, the new ZSI topology is suitable for the systems which require a high voltage boost ratio such as fuel cell, battery and photovoltaic systems.

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References


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