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Research Article

Performance Analysis of Switched Inductor Z-Source Inverter

Deepshikha[†*] and Rahul Kumar[†]

[†]Dept. of Electrical Engineering, D.I.T University, Dehradun, India

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Abstract

The conventional Z-source inverter can be used for boosting the output voltage for the various applications of dc–ac, ac–ac, dc–dc, and ac–dc power conversion. This paper presents the Z-source inverter with switched inductor instead of normal inductor of Z-network, which can provide high boost factor than the conventional Z-source inverter. This topology is implemented in MATLAB Simulink environment in order to evaluate the performance, the model is tested with different modulation indexes. The simple boost pulse width modulation scheme is used in the present work.

Keywords: *z-source inverter; shoot through state; switched inductor; modulation index; boost factor; shoot through duty ratio; simple boost pulse width modulation*

1. Introduction

The conventional voltage and current inverters have been awfully restricted because their obtainable output voltage range is limited, short-circuit occurs due to misgating and some other theoretical difficulties also occurs owing to their bridge type structures. The z-source inverter topology was proposed in 2002 to conquer the traditional inverters (F.Z. Peng, 2003) problems, in which the traditional dc-dc boost converter function has been favorably recommended into the inverter by an unequalled X-shape impedance network. As far as research concern in power electronics, the Z-source inverter topology has been considerably analyzed from different prospect (F.Z. Peng, 2002; Jih-Sheng Lai *et al*, 1996; A. Nabae *et al*, 1981), however in the open literatures the work related to its boost inversion ability and impedance network are barely reported.

The traditional Z-source inverter consists of an impedance network, having two capacitors and two inductors. In three phase Z-source inverter, there are nine switching states where as in the traditional voltage source inverter, there are eight switching states. So, the one extra state of the Z-source inverter is a shoot through state that determines the buck-boost feature to the inverter (J. Rodriguez *et al*, 2002; Poh Chiang Loh *et al*, 2007; Xiangyang Xing *et al*, 2014)

This way the Z-source inverter is different from voltage and current sources inverters (Jih-Sheng Lai *et al*, 1996). In low voltage energy sources such as fuel cell, photovoltaic etc, a recent technology is used in dc-dc power converts for growing power levels. It includes Switched-Capacitor (SC), Switched-Inductor (SL) and or combination of both (SC/SL). For this we can also consider the additive voltage cells, techniques without transformer and cascaded topologies. The most significant feature of these structures is acquiring great efficiency, large power density and simplest structures (C.L. Kuppuswamy *et al*, 2013). In this paper a switched-inductor Z-source inverter topology based on simple boost pulse width modulation control is implemented in the MATLAB Simulink. The model is tested with different modulation indexes.

2. Conventional Z-source Inverter

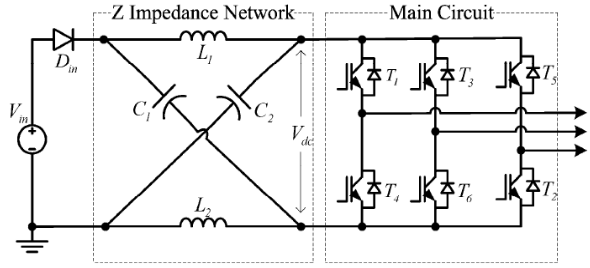

Fig: 1 Conventional Z-source inverter

The above figure shows the impedance network of the Z-source inverter includes two split inductors (L1 and L2) and two capacitors (C1 and C2) which are coupled in X-shape. The additional zero state can be made possible while the switching actions of upper and lower arms made possible, which determines the boost factor B for the voltage across the dc-link bus is expressed by:

$$B = \frac{V_{dc}}{V_{in}} = \frac{1}{1-2\frac{T_0}{T}} = \frac{1}{1-2D} \tag{1}$$

*Corresponding author: **Deepshikha**

Where, T_0 is the shoot-through interval during a switching cycle T and D is the duty ratio of each cycle, which is equal to T_0/T.

From eq. (1), it is observed that D is limited for the minimum scale of zero to the maximum of 0.5, in which the impendence network can execute the step-up dc-dc conversion from the input voltage V_{in} to the dc-link voltage V_{dc}.

In the practical applications, a higher value of D is required to provide a very high boost factor for the low voltage dc energy source. Thus, the Z-source inverter would have to be performed under the severe state of the shoot-through zero state. Accordingly, the modulation index, M of the main circuit will be reduced to a very low level, and the relations can be demonstrated by

$$M \leq 1 - D \tag{2}$$

Where,

$$M = \frac{\text{Amplitude of the modulation waveform}}{\text{Amplitude of the carrier waveform}} \tag{3}$$

The resulting low modulation index values gives an inadequate boost inversion ability with high THD values. As a consequence, the quality of the performance of ac output will be reduced significantly. For an optimal system design, the effective values of D have an upper limit, so the effective boost factor of Z-source impedance network is sincerely restricted according to (1).

These days the technologies are developing rapidly, thus the above disadvantages could be remarkable and also restricts the further applications of the Z-source inverter in several areas that needs an intense boost inversion capabilities for low voltage energy sources such as fuel cells, batteries and PV systems (Poh Chiang Loh *et al*, 2007; Miao Zhu *et al*, 2010; S.R. Aghdam *et al*, 2013).

3. Z-source Inverter with switched inductor

As illustrated in Fig. 2, the designed SL Z-source inverter is composed of four inductors (L1, L2, L3 and L4), two capacitors (C1 and C2), and six diodes (D1, D2, D3, D4, D5 and D6).The function of upper SL cell is performed by combining L1-L3-D1-D3-D5. The function of lower SL cell is performed by combining L2-L4- D2-D4-D6.

The purpose of using these pair of SL cells store and transfer the energy from the capacitors to the dc bus when the main circuit will be in the switching operation.

3.1. Operating principle

The operating principles of the impedance are same as that of the traditional Z-source impedance network as per their switching operation. The sub states of the impedance network are divided into the shoot-through state and the non-shoot-through state, respectively as shown in Fig. 3.

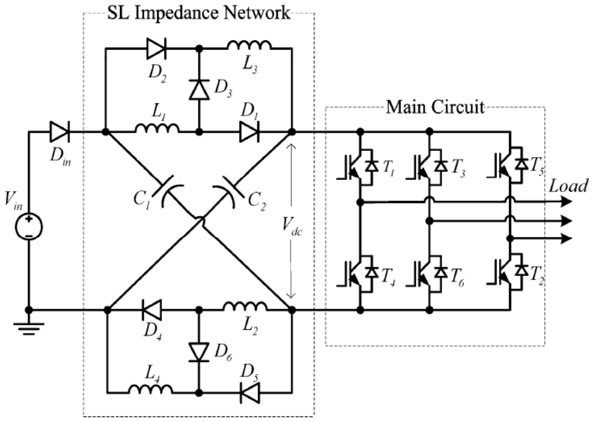

Fig. 2 Z-source inverter with switched inductor

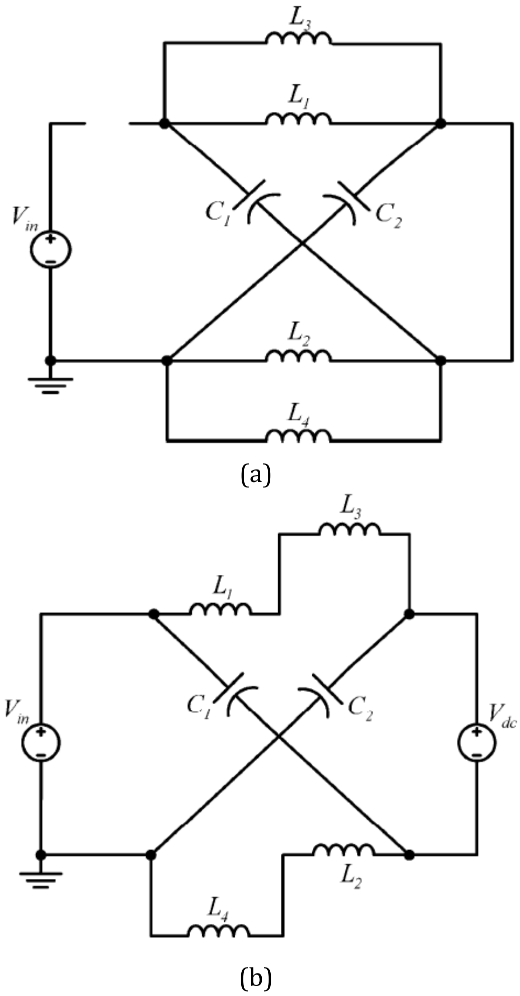

Fig: 3 Equivalent circuits. (a) Shoot through zero state (switching-on); (b) Non shoot through states (switching-off)

1) Shoot-through state

The above state is related to an extra zero state which is generated by the shoot-through operations of the top and bottom arms of the main circuit, and its equivalent circuit is shown in Fig. 3(a). In the course of this sub-state, S is on, while both D_{in} and D_o are in off-state. For the upper SL cell, when D1 and D2 are on, D3 will be off, inductors L1 and L3 are charged by capacitor C1 connected in parallel. For the lower SL cell, when D4 and D5 are on, D6 will be off, inductors L2 and L4 are charged by capacitor C2 connected in parallel. So, it is observed that both the upper and lower SL cells perform the similar function to absorb the energy stored in the capacitors.

2) Non-shoot-through state

The above mentioned state corresponds to the six active states and two zero states of the main circuit, and the equivalent circuit is shown in Fig. 3(b). In the course of this sub-state, S is off, while both Din and Do are on. For the upper SL cell, when D1 and D3 are off, D5 will be on. L1 and L2 are connected in series, and the stored energy is transferred to the main circuit. For the lower SL cell, when D4 and D5 are off, D5 is on. L3 and L4 are connected in series, and the stored energy is transferred to the main circuit. At the same moment, to supplement the consumed energy of C1 and C2 during the shoot-through state, C1 is charged by V_{in} via the lower SL cell, and C2 is charged by Vin via the upper SL cell.

4. Derivation of boost factor of ZSI-SI

For the mathematical derivation it is convenient to assume all the inductance (L) and capacitance(C) have the same value respectively; consequently, both the equivalent circuits in Fig. 5 shows the symmetrical characteristics. In addition, since C1 and C2 are sufficiently large, thus, in the steady state, we have

$$V_{C1} = V_{C2} = V_C \tag{4}$$

When the switch is in ON state the inductor current i_{L1} increases and decreases while it is in OFF state. The corresponding voltage across L1, $V_{L1\text{-}ON}$ is equal to V_C, under the switching ON condition. By introducing the volt–second balance principle to L1, we can obtain the equivalent voltage across L1 while switch is OFF, $V_{L1\text{-}OFF}$, which can be expressed by

$$\begin{aligned} V_{L1-OFF} &= \frac{D}{1-D} V_C \\ &= V_{L3-OFF} \end{aligned} \tag{5}$$

The inductor current i_{L3} increases during switching ON and decreases during switching OFF. The corresponding voltages across L3 are equal to V_{C1} and $-(V_{C2} - V_{in} + V_{L1\text{-}OFF})$.

By introducing the volt–second balance principle to L3, we obtain

$$\begin{aligned} &DTV_{C1} = (1-D)T(V_{C2} - V_{in} + V_{L1-OFF}) \text{ or} \\ &DTV_{in} = (1-D)T(V_C - V_{in} - \frac{D}{1-D} V_C) \end{aligned} \tag{6}$$

Hence,

$$\begin{aligned} V_C &= \frac{1-D}{1-3D} V_{in} \\ &= V_{C1} = V_{C2} \end{aligned} \tag{7}$$

During switching OFF, C1, L1, L3, and the voltage source Vdc form a close loop; therefore obtain

$$V_C = V_{dc} + V_{L1-OFF} + V_{L3-OFF} \tag{8}$$

So,

$$V_{dc} = \frac{1+D}{1-3D} V_{in} = BV_{in} \tag{9}$$

The boost factor of the SL Z-source impedance, B is thus expressed by

$$\begin{aligned} B &= \frac{1+D}{1-3D} \\ &= \frac{1+\left(\frac{T_0}{T}\right)}{1-3\left(\frac{T_0}{T}\right)} \end{aligned} \tag{10}$$

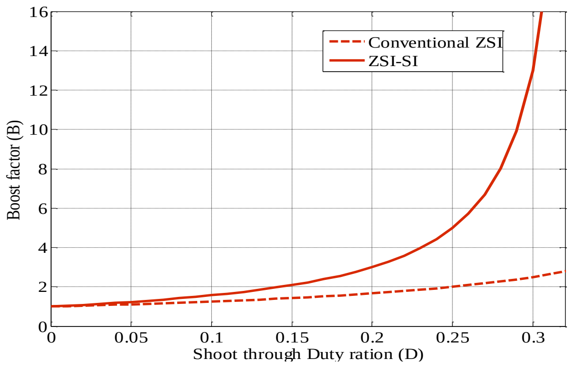

Fig: 4 Boost ability comparison of the classical Z-source impedance network and the Z-source impedance network with switched inductor

To compare the individual boost ability of classical Z-source impedance network and the Z-source impedance network with switched inductor, the curves of the boost factor B and duty ratio D is shown in Fig. 4 respectively. We can observe from the curves of Fig. 4 that the boost ability of the proposed SL impedance network is significantly increased as compared to that of the classical Z-source impendence network.

5. Modulation scheme of ZSI-SI

The above figure illustrates the simple control method that uses a straight line equal to or greater than the peak value of the three phase references to control the shoot-through duty ratio in a traditional sinusoidal PWM. The Z-source inverter maintains the six active states unchanged as the traditional carrier based PWM control, for this simple boost control (C.L. Kuppuswamy *et al*, 2013), the resultant shoot through duty ratio decreases with the increase of the modulation index, M. The limitation of maximum shoot-through duty ration of simple boost control is (l-M), so it reaches zero at a modulation index of one.

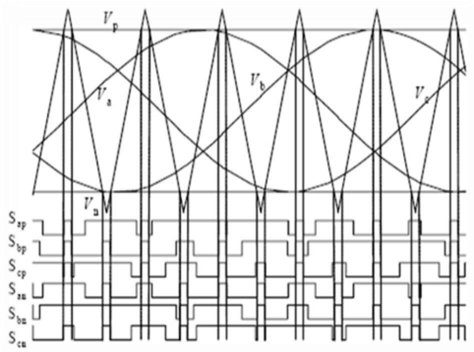

Fig: 5 Simple boost PWM

So, to obtain an output voltage having high voltage gain, a small modulation index value has to be used. Though, lower modulation index values will results in higher voltage stress on the devices. Based on the (1) and (10), define the voltage gain G as

$$G = \frac{V_{ac}}{V_{in}/2} = MB = \frac{M(2-M)}{3M-2} \tag{11}$$

For the conventional Z-source inverter, based on (1) the voltage gain G is defined as,

$$G = \frac{V_{ac}}{V_{in}/2} = MB = \frac{M}{2M-1} \tag{12}$$

From (11) and (12), it is clear that voltage conversion gain with switched inductor Z-source inverter is greater than the voltage gain with conventional Z-source inverter.

6. Simulation Results

In order to evaluate the performance of Z-source inverter with switched inductor concept, the model is implemented in the MATLAB Simulink by considering the input DC voltage (V_{in}) of 150 V, Z-network consists of L1 = L2 = 5 mH and C1 = C2 = 1000 μF. The three phase resistive load of 5 kW is selected.

Fig. 6, shows the Simulink model implemented for the Z-source inverter with switched inductor in the MATLAB Simulink. It has been examined for the three phase resistive load of 5 kW by using simple boost pulse width modulation. The switching frequency is chosen as 1 kHz.

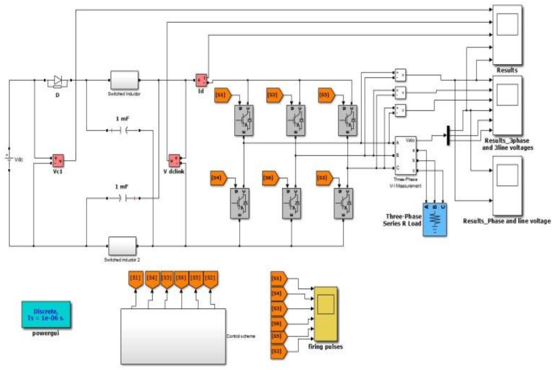

Fig: 6 Simulink model of Z-source inverter with switched inductor

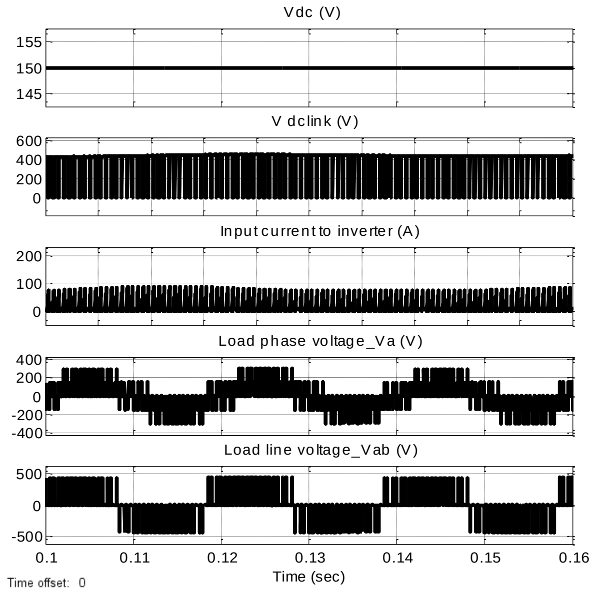

Fig: 7 Simulation results of ZSI-SI showing (a) input DC voltage, (b) DC link voltage after Z-network, (c) Input current to the inverter, (d) Load phase voltage, (e) Load line voltage

The simulated scope results for the modulation index of 0.8 are shown in Fig. 7. From the results it has been clear that the output phase voltage is greater than the input DC voltage. That means output voltage is boosted to the higher level as 295 V of peak magnitude, whereas input DC magnitude is of 150 V. From (11), the voltage gain can be calculated as 3.93 for the above simulation. Fig. 8, shows the all the three phase load line and phase voltages.

6.1. Performance of ZSI with switched inductor for different modulation index values

The model is examined for the different modulation index values in order to evaluate the performance. The modulation index is varied from 0.6 to 0.9 and the captured results are shown in Fig. 9-12.

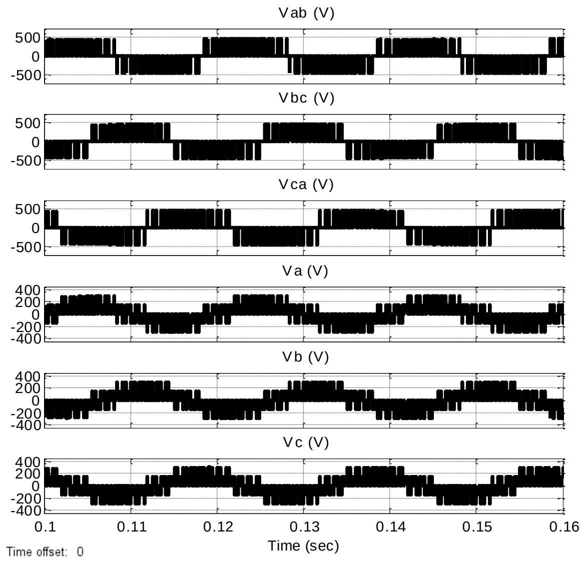

Fig: 8 Scope results of ZSI-SI showing three phase load line and phase voltages

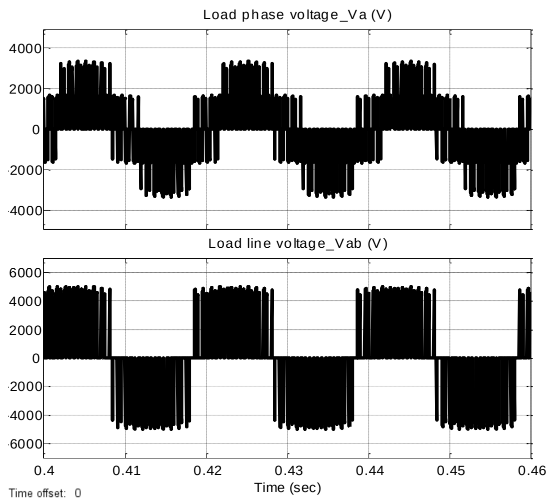

Fig:9 Phase and line voltage waveforms with modulation index of 0.6

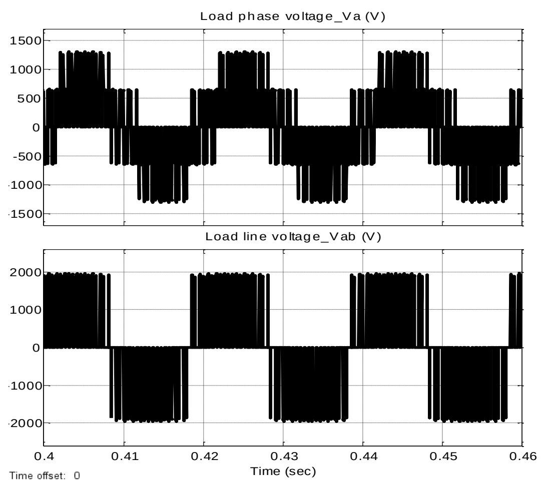

Fig: 10 Phase and line voltage waveforms with modulation index of 0.7

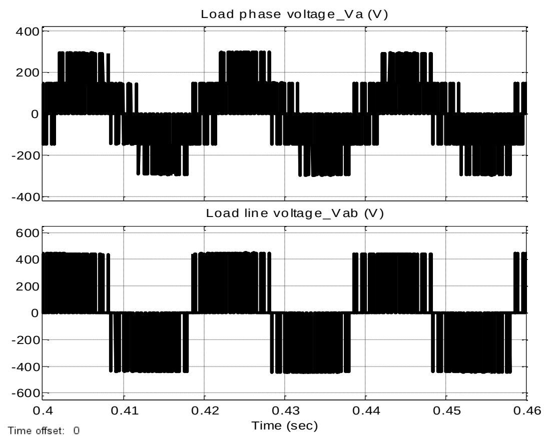

Fig: 11 Phase and line voltage waveforms with modulation index of 0.8

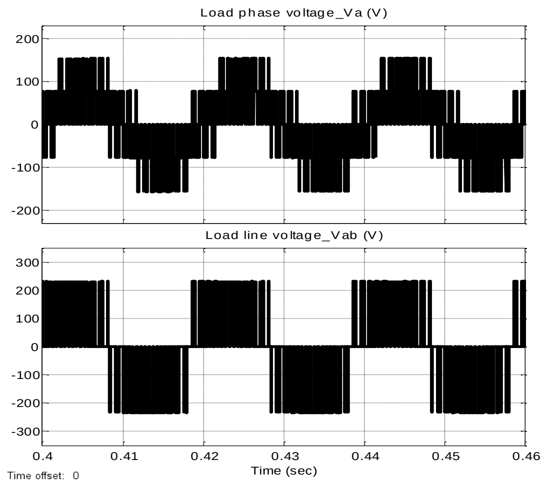

Fig: 12 Phase and line voltage waveforms with modulation index of 0.9

As modulation index is increased the output load voltage is decreased because of the decreased shoot through interval same as that of conventional Z-source inverter. The results are summarized in the following Table 1.

Table 1 Peak value of load phase and line voltages with different modulation index values

Modulation Index (m_a)	Peak load voltage	
	Phase (V)	Line (V)
0.6	3300.00	4900.00
0.7	1300.35	1940.15
0.8	295.51	440.20
0.9	154.62	235.56

Conclusions

The Z-source inverter with switched inductor instead of normal inductor of Z-network share the same operation condition and can be integrated into one magnetic core, which helps to reduce the size of magnetic components. From the simulation results, it has been observed that ZSI-SI can provide the higher boost factor and a very short shoot-through zero state is required to obtain high voltage conversion ratios as varying the modulation index values.

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