Comparative Study of Z-Source Inverter

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ABSTRACT
A comparative study of few z-source inverter topologies with control methods are compared and presented in this paper. Z-source inverter uses shoot-through state which boosts input voltage, improves reliability of converter. This is useful in some applications like electrical drives, power generation technologies such as fuel cells, solar photovoltaic cells, wind turbines and commercial application like hybrid electric vehicles, etc. The ZSI has few drawbacks like decrease in efficiency, unidirectional power flow, light-load operation, higher inrush current during starting. To overcome these limitations various modifications have been suggested by researchers in the basic topology of ZSI. A comparative study of these topologies with simulation results is presented in this paper.

Keywords
Voltage Source Inverter (VSI); Current Source Inverter (CSI); Z-Source Inverter (ZSI).

1. INTRODUCTION
Voltage source inverter (VSI) and Current source inverter (CSI) are the two widely used inverter configurations in various industry and power sector applications. Fig. 1, and 2 shows basic configuration of VSI and CSI respectively. The capacitor and inductor are energy storage devices. The capacitor resists a change in voltage and acts as constant voltage source. The inductor resists a change in current and it is used to reduce the ripple in output current of converter. [1].

![Fig 1: VSI topology](image1)

![Fig 2: CSI topology](image2)

The VSI and CSI with the basic configurations have drawback such as its output voltage cannot be increased than input DC voltage, their circuit cannot be interchanged, they are susceptible to electromagnetic interference. The basic topology of VSI and CSI do not use the buck-boost characteristics, they are either a boost or a buck converter and cannot be buck-boost converter. For some applications buck as well as boost operation is essential. A dc-dc converter is required to fulfill this demand with basic topologies. This increases the stages of power conversion, switching and conduction losses reducing the overall efficiency. This leads to complex control of the complete system thus overall cost of the system also increases [1-2].

To overcome these limitations various Z-Source topologies have been developed. It has both capacitor and inductor, the purpose of the capacitor is to absorb the voltage ripple and maintain a constant voltage and the purpose of the inductor is to absorb the current ripple and maintain a constant current. ZSI uses the shoot-through state to boost the input voltage which improves the inverter reliability and expands application field. ZSI has some drawbacks like higher start up inrush current, unidirectional power flow, a discontinuous input current and higher Z-network capacitor voltage that results in decrease in inverter efficiency. To overcome these limitation of basic ZSI topology, many modifications have been suggested and implemented by the researchers. A comparative study of few modified topologies of Z-source inverter is presented in this paper.

The Z-source inverter has several advantages as compare to traditional inverter: • DC link provides constant source.
• Miss-firing of switches sometimes are also acceptable.
• ZSI has both buck-boost operating property.
• Less affected by the electromagnetic interference.
• Harmonic distortion is low.

2. Z-SOURCE INVERTER
Fig. 3 shows the basic topology of ZSI where two capacitors and inductors are used. The inductor $L_1$, $L_2$ and capacitors $C_1$, $C_2$ connected in X-shape to deliver an impedance source coupled between the DC mains and the inverter. The DC main source may be a battery, solar photovoltaic cell, fuel cell etc. while the inverter may be single-phase or three-phase depending upon the type of load.

![Fig 3: Generalized structure of the Z-source Inverter](image3)

The Z-Source is useful in all dc-ac, dc-dc, ac-dc and ac-ac power conversion forms. To describe the operating principle of ZSI, an example of a Z-source inverter application in dc-ac power conversion for solar photovoltaic cell is presented.

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Fig. 4: Basic VSI for solar photovoltaic applications

Fig. 5: Basic ZSI for solar photovoltaic applications

Fig. 6: Equivalent circuit of Single-Phase ZSI

The single phase Z-source inverter has five permissible switching stages while in voltage source inverter there are only four switching stage occurs. The one additional stage is shoot-through state, which is present in Z-source inverter. If the shoot-through stage occurs in voltage source inverter, the switches of inverter legs get damaged. The other four stages which occur in both Z-source inverter and voltage source inverter are active stage and zero stage. The active stage occurs when the dc voltage is impressed across the load and the zero stage occurs when the load terminal gets shorted through either uppers or lowers two switches of inverter legs.

Table 1 provides the details of switching states of power switches and corresponding state of output voltage [3-5].

<table>
<thead>
<tr>
<th>Switching States</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>Output Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active states</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>Finite Voltage</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Zero State</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>Zero</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Shoot Through State</td>
<td>S1</td>
<td>S2</td>
<td>S3</td>
<td>S4</td>
<td>Zero</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

However, the single-phase Z-source inverter has one additional shoot-through stage. The load terminal gets shorted through both the upper and lower device of any one of the leg or get shorted by both legs of the inverter. This shoot-through stage is generated by three different ways: shoot-through via first phase leg, shoot-through via other or second phase leg and shoot-through via combination of both phase legs. This unique buck-boost property is occurring during the shoot-through stages of the inverter and boosts the output voltage level [2-5].

Fig. 7: Shoot-through switching state

For convenience of mathematical derivation, it is assumed that the inductors \(L_1\) and \(L_2\), and capacitors \(C_1\) and \(C_2\) connected in X-shape have the same values as inductance \(L\) and capacitance \(C\), respectively. By assuming this the Z-source becomes symmetrical. Due to this

\[
V_{C1} = V_{C2} = V_C \quad V_{L1} = V_{L2} = V_L \quad (1)
\]

When the inverter bridge for the interval of shoot-through stage of switching cycle, from the equivalent circuit (fig. 7), it is understood that

\[
V_L = V_C \quad V_d = 2V_C \quad V_i = 0 \quad (2)
\]

Table 1: Switching States of Single-Phase ZSI
With the QZSI and ZSI, the unique LC and diode network connected to the inverter bridge modifies the operation of circuit, allowing the shoot-through state. This network effectively protects the circuit from damage when the shoot-through occurs and by using the shoot-throttle state, the Quasi Z-source network boosts the dc-link voltage. The major differences between the ZSI and QZSI are the QZSI drawscontinuous current from the source. While the ZSI draws-discontinuous current and the voltage on capacitor C2 is greatly reduced. The continuous and constant dc current drawn from the source with this QZSI makes system well-suited for PV power conditioning systems.

The boost factor of the QZSI is same as ZSI,
\[
B = \frac{1}{1 - 2D} \geq 1
\]

Advantages of Quasi Z-Source Inverter (QZSI)
- Continuous input current.
- Low start-up inrush current.
- Reducing passive component rating and improving input profile.
- Reduce voltage stress on capacitor.

4.2 Switched Inductor Z-Source Inverter (SL-ZSI)
In Switched Inductor Z-source Inverter (SL-ZSI), the impedance type power inverter is developed based on the classical Z-source inverter. Fig. 10 shows the equivalent circuit of SL-ZSI. To enhance voltage adjustability, the SL-ZSI inverter employs a unique switched-inductor impedance network which is coupled between the main circuit and the power source. Compared with the classical Z-source inverter, SL-ZSI increases voltage boost inversion ability significantly. To obtain high voltage conversion ratio, only a very short shoot-through zero state is required, which is advantageous for improving the output power quality of the main circuit.
two capacitors \((C_1\text{ and } C_2)\) and four diodes \((D_{in}, D_1, D_2\text{ and } D_3)\). The configuration is shown in Fig. 11.

![Fig. 11: Switched-Inductor Quasi-ZSI (SL-QZSI)](image)

In comparison to the SL-ZSI, for the same input and output voltages, the SL-QZSI provides higher output voltage, continuous input current, a common ground with the dc source, reduced the passive component count, lower shoot-through current and improves reliability and lower current stress on inductors and diodes. The SL-QZSI suppresses inrush current at startup, which might damage the power devices. Compared with a QZSI, the SL-QZSI adds only three diodes and one inductor, and the boost factor increases from \(1/(1−2D)\) to \((1+D)/(1−2D)\).

The boost factor of the SL-QZSI is given by

\[
B = \frac{1 + D}{1 - 3D} \geq 1
\]  

Advantages of Switched-Inductor Quasi-ZSI (SLQZSI)

- continuous input current.
- It can suppress inrush current at start-up.
- reduced passive component count.
- reduced voltage stress on capacitor.
- lower current stress on inductor and diode.

4.4 Comparison between ZSI, QZSI, SL-ZSI and SL-QZSI.

![Fig. 12: Duty cycle against boost factor](image)

4.3 Switched Inductor Quasi Z-Source Inverter (SL-QZSI)

The design configuration is modified as compare to previous topologies. The SL-QZSI uses three inductors \((L_1, L_2\text{ and } L_3)\).

![Fig. 10: Switched Inductor ZSI (SL-ZSI)](image)

As shown in Fig. 10, SL-ZSI consist of four inductors \((L_1, L_2, L_3\text{ and } L_4)\), two capacitors \((C_1\text{ and } C_2)\) and six diodes \((D_1, D_2, D_3, D_4, D_5\text{ and } D_6)\). The top cell consists of \(L_1 - L_2 - D_1 - D_3 - D_5\) and the bottom cell consists of \(L_3 - L_4 - D_2 - D_4 - D_6\). To store and transfer the energy from capacitor to dc bus under the switching state of the main circuit both the cells are used. This topology is much different compared to other Z-source inverters from the viewpoint of circuit structures and operating principles. Only six diodes and two inductors are added compared to the classical Z-source inverter and the boost factor has been increased from \(1/(1−2D)\) to \((1+D)/(1−3D)\).

The boost factor of the SL-ZSI expressed as

\[
B = \frac{1 + \frac{T_o}{T}}{1 - 3\frac{T_o}{T}} = \frac{1 + D}{1 - 3D} \geq 1
\]  

Advantages of Switched Inductor ZSI (SL-ZSI) are

- achieved high boosting capability.
- high power density.
- improved dependence between voltage gain and modulation index.
- only a very short shoot through zero state is required to obtain high voltage conversion ratio.

Disadvantages of Switched Inductor ZSI (SL-ZSI)

- SL-ZSI adds six diodes and two inductors, compared with the classical ZSI, which increases size, cost, and loss.
- SL-ZSI does not share a dc ground point between the source and converter.
- the input current is discontinuous, and it requires a decoupling capacitor bank.
- SL-ZSI cannot suppress the inrush current and the resonance introduced by Z-source inductors and capacitors at start-up, and the resulting voltage and current spike can damage the devices.

To overcome these drawbacks of SL-ZSI a new topology is proposed named Switch Inductor Quasi Z-Source Inverter. The details of this topology are explained in the next section of the paper.

Table 2: Comparison of various ZSI topologies

<table>
<thead>
<tr>
<th>topologies and elements required</th>
<th>ZSI</th>
<th>QZSI</th>
<th>SL-ZSI</th>
<th>SL-QZSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Elements</td>
<td>2-L, and 2-C</td>
<td>2-L, 2-C and one diode</td>
<td>4-L, 2-C and six diodes</td>
<td>3-L, 2-C and four diodes</td>
</tr>
<tr>
<td>Constant input current</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Start-up inrush current</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Boost Factor</td>
<td>$\frac{1}{1 - 2D}$</td>
<td>$\frac{1}{1 - 2D}$</td>
<td>$\frac{1 + D}{1 - 3D}$</td>
<td>$\frac{1 + D}{1 - 2D - D^2}$</td>
</tr>
</tbody>
</table>

Fig. 12 shows the duty cycle against boost factor comparison of various ZSI topologies and the Table 2 shows the comparative study of ZSI topology.

5. CONTROL TECHNIQUES

Fig. 13: Sine PWM Control Method

Fig. 13 explains the principal of sine PWM technique useful for controlling the inverter output. Power frequency sine signal and triangular carrier signal are compared to generate switching pulses for the power devices. Amplitude and frequency modulation index can be controlled as per requirement to control the inverter output voltage and THD contents. A switching frequency of 5 kHz is used to control inverter power devices.

6. SIMULATION RESULTS

Various topologies of ZSI are simulated using MATLAB Simulink and the results are presented in this section.

Fig. 14: Block Diagram of ZSI Simulations

Fig. 14 shows the basic block diagram of ZSI simulations study. The simulation parameters of various ZSI topologies, presented in this paper, are shown in Table 3. From comparison point of view, the ratings of inductors and capacitors are selected as same for these topologies. Fig. 15 shows the simulation results of various type of ZSI. These are the steady-state results. Being the same inverter (1-ph 2-level) configuration is used for all the topologies including load parameters, the nature of output voltage and response remains almost same. The difference lies in the inrush current drawn from the source. Fig. 16-19 shows the startup inrush current for these various topologies.

Table 3: Simulation Parameters of ZSI and its types

<table>
<thead>
<tr>
<th>Input DC Voltage</th>
<th>100 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZSI</td>
<td>$C_1 = C_2$ = 1000 µF</td>
</tr>
<tr>
<td></td>
<td>$L_1 = L_2$ = 160 µH</td>
</tr>
<tr>
<td>Boost Converter</td>
<td>$C_3$ = 500 µF</td>
</tr>
<tr>
<td></td>
<td>$I_3$ = 120 µH</td>
</tr>
<tr>
<td>Load</td>
<td>R = 40 Ω</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>5 kHz</td>
</tr>
</tbody>
</table>

Fig. 15: Simulation Result of ZSI Topology

Fig. 16: ZSI
Fig. 17: QZSI
Fig. 18: SL-ZSI
Fig. 19: SL-QZSI

Fig. 16-19: Simulation results indicating starting inrush current for various ZSI topologies

7. CONCLUSION

Various topologies of Z-source inverter are presented in this paper for implementing dc-to-ac power conversion. A comparative study of four topologies namely basic Z-source inverter, Quasi Z-source inverter, switched inductor Z-source inverter and switched inductor Quasi Z-source inverter are presented with respect to the components required, inrush current, boost factor. It is seen that the SL-QZSI topology provides better output voltage boost with moderate boost factor. This topology also has an added advantage with moderate inrush current with comparatively less number of components requirement as in QZSI and SL-ZSI. Z-source inverter employs a unique impedance network which coupled between the inverter main circuit and the power source, thus
providing added features that cannot be observed in the basic voltage-source and current-source converter configuration. The Z-source converter overcomes the limitations of the voltage-source converter and current-source converter and provides a better power conversion concept. The Z-source model can be applied to almost all dc-to-ac, ac-to-dc, ac-to-ac, and dc-to-dc power conversion.

8. REFERENCES