Comparitive Study of Z-Source Inverter

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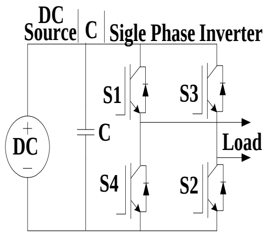
ABSTRACT
A comparative study of few z-source inverter topologieswith control methods are compared and presented in this paper.Z-source inverter uses shoot-through state which boosts input voltage, improves reliability of converter. This is useful in some applications like electrical drives, power generation 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 limitationsvarious modifications have been suggested by researchers in the basic topology of ZSI. Acomparative 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. INTRODUCTON
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].



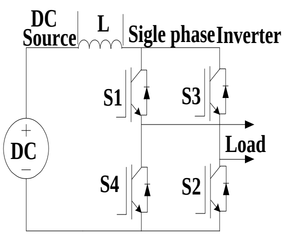


Fig 1: VSI topology **Fig 2:CSI topology**

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 drawback 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. Acomparative 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.

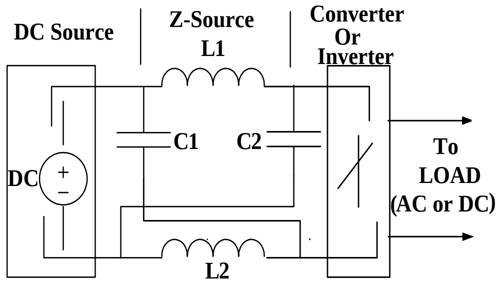


Fig. 3: Generalized structure of the Z-source Inverter

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 applicationin dc-ac power conversion for solar photovoltaic cell is presented.

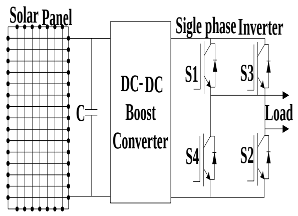


Fig. 4: Basic VSI for solar photovoltaic

Fig. 4 shows the VSI for solar photovoltaic cell applications. Because solar cell usually produces a low voltage at the output; the additional dc-dc boost converter is needed to boost the output voltage because the voltage source inverter cannot produce the higher ac voltage as compared to the input dc voltage.

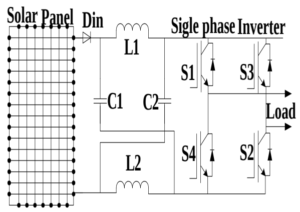


Fig. 5: Basic ZSI for solar photovoltaic

Fig. 5 shows Z-Source Inverter for solar photovoltaic cell applications, which produce ac output voltage greater than dc input voltage which generated by the PV cell. The diodeD_{in} is used in series with the solar PV cell to prevent the solar PV cell from reverse current flow [2-7].

3. OPERATING PRINCIPLEAND EQUIVALENT CIRCUIT OF ZSI

The characteristic feature of the Z-source inverter has unique impedance network coupled between dc source and inverter. The output ac voltage can be controlled greater or less than the dc input voltage.In other word, the Z-Source Inverter is the buck-boost inverter that gives the wide range of out-put voltage. Fig. 6 shows the equivalent circuit of single-phase Z-source inverter [4-8].

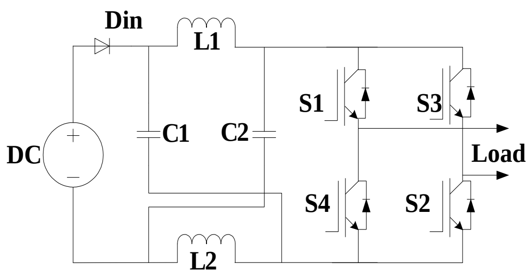


Fig. 6: Equivalent circuit of Single-Phase ZSI

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 1:Switching States of Single-Phase ZSI.

Switching States	S1	S2	S3	S4	Output Voltage
Active states	1	1	0	0	Finite Voltage
	0	0	1	1	
Zero State	1	0	1	0	Zero
	0	1	0	1	
Shoot Through State	1	S2	S3	1	Zero
	S1	1	1	S4	
	1	1	1	1	

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].

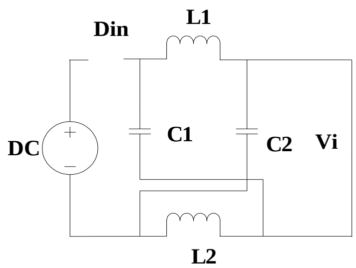


Fig. 7: Shoot-through switching state

Fig. 7 shows the equivalent circuit of shoot-through stage of single-phase ZSI, where the inverter bridge is short circuited by the upper and lower switching devices. The sum of two capacitor voltages is greater than dc source voltage. The diode D gets reverse biased and the capacitor charges the inductor.

For convenience of mathematical derivation, it is assumed that the inductors L_1 and$L_2$and capacitors $C_1$and C_2connected 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

$$\mathrm{V_{C1} = V_{C2} = V_C} \quad \mathrm{V_{L1} = V_{L2} = V_L} \quad (1)$$

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

$$\mathrm{V_L = V_C} \quad \mathrm{V_d = 2V_C} \quad \mathrm{V_i = 0} \quad (2)$$

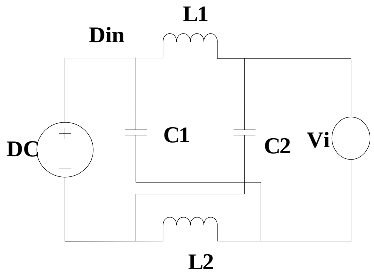


Fig. 8: Non-Shoot-through switching state

Fig. 8 shows the equivalent circuit of non-shoot through stage of single-phase Z-source inverter, where the two stages occurs namely active state and zero state. In active stage, the dc voltage is impressed across the load. While in zero state, the dc voltage is not impressed (i.e. zero) across the load, the inverter bridge get short circuit by either upper or lower switching device. When the inverter bridge is in the non-shoot through stage of switching cycle, from the equivalent circuit (fig. 8), it can be written as

$$V_L = V_{in} - V_C V_d = V_{in}$$

$V_i = V_C - V_L = 2V_C - V_{in}$ (3)

The Z-source inverter boosts the output voltage by the boost factor given as

$$B = \frac{1}{1-2\frac{T_0}{T}} = \frac{1}{1-2D} \quad (4)$$

where, D = Duty cycle.

The boost factor B as expressed in (4) can be controlled by duty cycle of the shoot-through state over the non-shoot through state using inverter control method.

The Z-source inverter has following drawbacks

- high start-up inrush current
- discontinuous input current
- unidirectional power flow
- higher voltage stress on the switches and capacitors

To overcome these drawbacks of ZSI, there are many modificationssuggested in the basic configuration by the researchers.

4. TOPOLOGIES OF ZSI

Many modificationshave been suggested and implemented in the basic structure of ZSI. The modifications are in number of component (inductor, capacitor and diode) used in the circuit, structural arrangement etc. [7-13].

4.1 Quasi Z-Source Inverter

The Quasi-ZSI comprisesalmost all the advantages of the ZSI, and it overcomes some limitations of basic ZSI topology. Fig. 9 shows the equivalent circuit of QZSI. It has two inductors and capacitors namelyL_1, L_2 andC_1 , C_2 respectively same as in the ZSI with additional one diode D is used. It also has five permissible switching states as given in Table 1. QZSI has the unique advantages of lower component ratings and constant dc current from the source. Despite ofthese advantages, the ZSI has some obvious drawbacks, such as discrete input current, which leads to low utilization and damage to the dc source, large voltage stress across the switches and capacitors, huge inrush current, and a lower modulation index for high-gain output voltage that leads to poor output voltage waveform quality. With the introduction of quasi-ZSIs (QZSIs), the classical ZSI's shortcomings are solved. This topology improves the input current profile and reduces the passive component ratings.

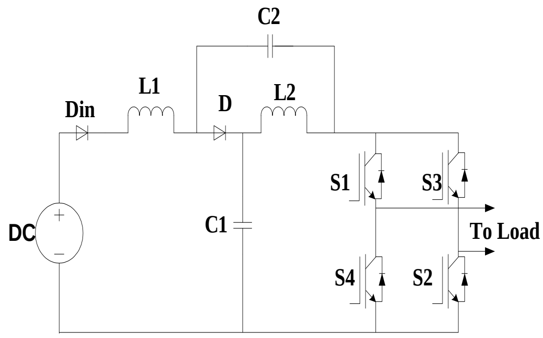


Fig. 9: Quasi Z-Source Inverter (QZSI)

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-though 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 drawsdiscontinuous current and the voltage on capacitor C_2 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,

$$B = \frac{1}{1-2\frac{T_0}{T}} = \frac{1}{1-2D} \geq 1 \quad (5)$$

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.Toobtain 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.

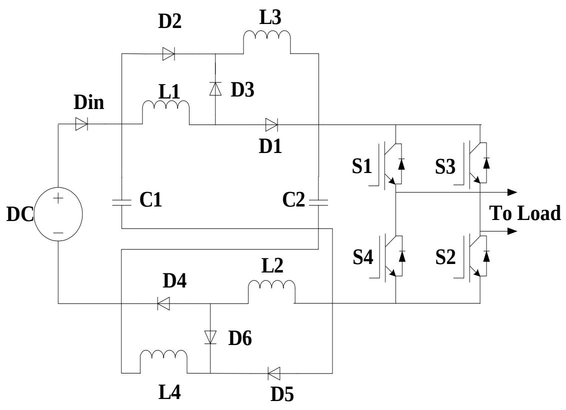


Fig. 10: Switched Inductor ZSI (SL-ZSI)

As shown in Fig. 10, SL-ZSI consist of four inductors (L_1,L_2,L_3andL_4), two capacitors (C_1 and C_2) and six diodes (D_1,D_2, D_3, D_4, D_5andD_6). The top cell consists of$L_1 - L_3 - D_1 - D_3 - D_5$ and the bottom cell consists of$L_2 - L_4 - D_2 - D_4 - D_6$. 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

$$B = \frac{1 + \frac{T_0}{T}}{1 - 3\frac{T_0}{T}} = \frac{1 + D}{1 - 3D} \geq 1 \qquad (6)$$

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.

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,$L_2$and L_3), two capacitors (C_1 andC_2) and four diodes (D_{in},D_1,D_2 and D_3). The configuration is shown in Fig. 11.

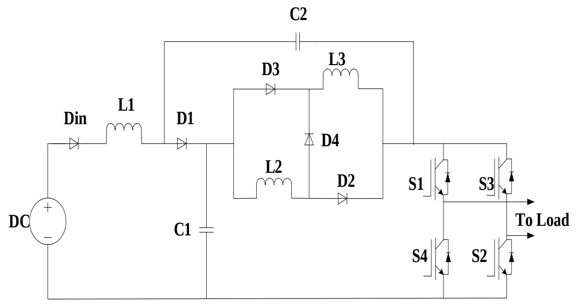


Fig. 11: Switched-Inductor Quasi-ZSI (SL-QZSI)

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 currentand improves reliability and lower current stress on inductors and diodes.The SL-QZSIsuppresses 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 −D2).

The boost factor of the SL-QZSI is given by

$$B = \frac{1 + D}{1 - 2D - D^2} \geq 1 \qquad (7)$$

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.

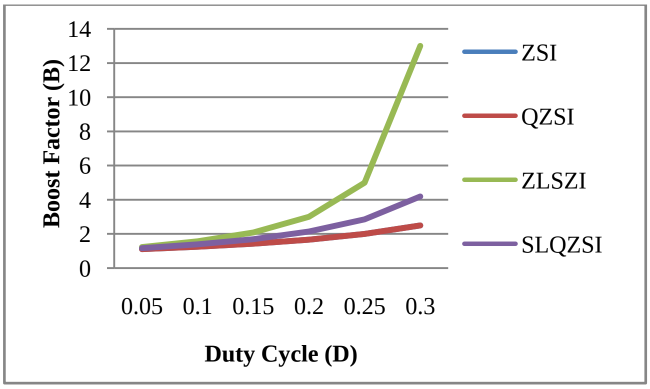


Fig. 12: Duty cycle against boost factor

Table 2: Comparison of various ZSI topologies

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

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

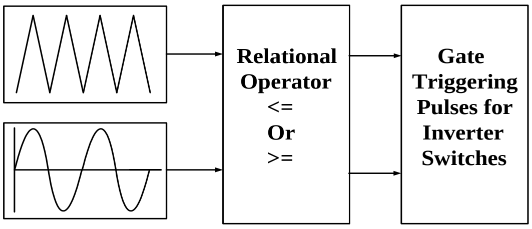


Fig. 13: Sine PWM Control Method

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 out-put voltage and THD contents. A switching frequency of 5 kHz is used to control in inverter power devices.

6. SIMULATION RESULTS

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

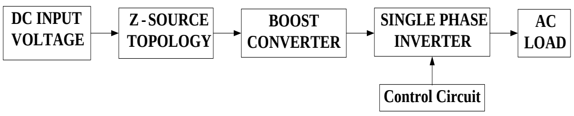


Fig. 14: Block Diagram of ZSI Simulations

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 out-put voltage and response remains almost same. The difference lies in the inrush current drawn from the source. Fig. 16- 19shows the startup inrush current for these various topologies.

Table 3: Simulation Parameters of ZSI and its types

Input DC Voltage	100 V	
ZSI	$C_1 = C_2$	1000 µF
	$L_1 = L_2$	160 µH
Boost Converter	C_3	500 µF
	L_3	120 µH
Load	R	40 Ω
Switching Frequency	5 kHz	

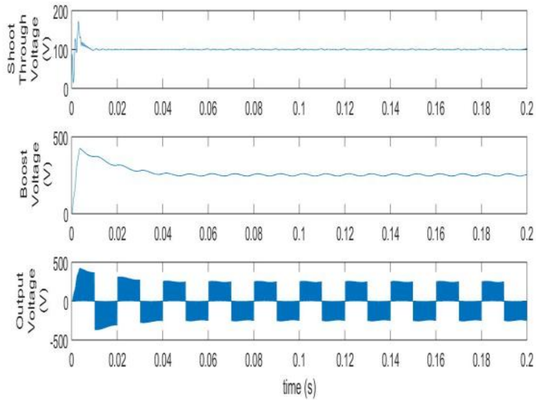


Fig. 15: Simulation Result of ZSI Topology

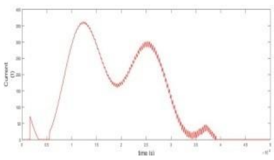


Fig. 16: ZSI

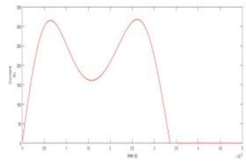


Fig. 17: QZSI

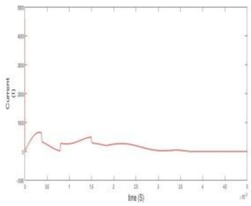


Fig. 18: SL-ZSI

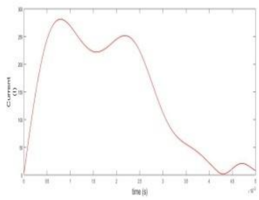


Fig. 19: SL-QZSI

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

7. CONCLUSION

Various topologies of Z-source inverter are presented in this paperfor 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**.**

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