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# Topologies of Single Phase Z Source Inverters for Photovoltaic Systems

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***Abstract*—This paper deals with a new family of high voltage boost inverter topologies for single phase systems. The proposed topologies are derived from quasi Z source inverter (qZSI), switched inductor Z source inverter (SLZSI) and switched-inductor quasi Z source inverter (SLqZSI) which can realize buck/boost, inversion and power conditioning in a single stage with improved reliability. They provide continuous input current, reduced voltage stress on capacitors and lower current stress on inductors with high voltage boost inversion ability. Proposed topologies are analyzed in the steady state and their performances are validated using simulated results obtained in MATLAB/Simulink environment.**

***Keywords— Boost inversion ability, quasi-Z-source inverter, switched inductor Z-source inverter, switched inductor quasi Z-source inverter.***

## I. Introduction

Z source inverters (ZSI) are single stage power converters with voltage buck boost capabilities that have been proposed for various applications like solar photovoltaic systems, wind energy/fuel cell systems, electric vehicles, UPS etc. The Z (impedance) source network is placed between dc voltage source and the inverter and it boosts the dc voltage [1]. Z source network which exhibits voltage boosting performance is analyzed through signal flow graph technique [2, 3].

Basic quasi, switched inductor Z source/quasi Z source inverter topologies are presented in [4-6] for additional voltage boosting. A detailed literature review about various topologies of Z source power converters, their control and modulation technique are presented in [7, 8].

Passive LC and LCL filters are connected at the inverter terminals for harmonic reduction as discussed in [9, 10]. This paper addresses about various new topologies of single phase Z source inverters. Simulations are carried out for analyzing the voltage boost and total harmonic distortion characteristics of the prospective topologies in MATLAB environment.

## II. Circuit Analysis of Quasi Z Source Single Phase Inverter

Quasi Z source single phase inverter (qZSI) shown in fig. 1 has the following features: (1) the qZSI draws a continuous constant dc current from the source while the ZSI draws a discontinuous current and (2) the voltage on capacitor C1 is greatly reduced, and hence lower capacitor rating; [4]

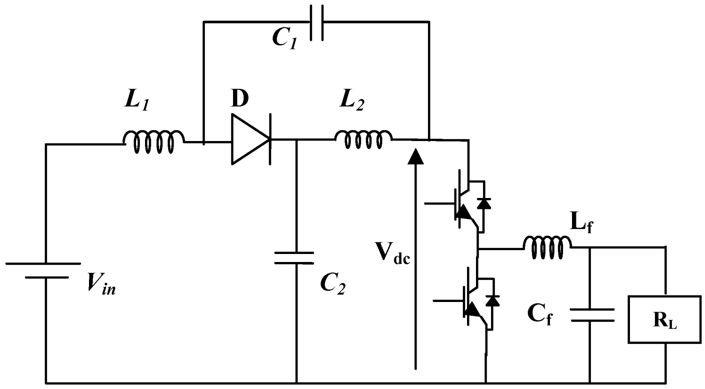


Fig. 1. Quasi Z source single phase inverter

Assuming that during one switching cycle, $T$

$$v_{L1} = V_{in} - V_{C1}, v_{L2} = -V_{C2} \quad (1)$$

$$v_{dc} = V_{C1} - v_{L2} = V_{C1} + V_{C2} \ , \ v_{diode} = 0 \quad (2)$$

$$v_{L1} = V_{C2} + V_{in}, \quad v_{L2} = V_{C1} \quad (3)$$

$$v_{dc} = 0 \quad , \quad v_{diode} = V_{C1} + V_{C2} \quad (4)$$

At steady state, the average voltage of the inductors over one switching cycle is zero.

The voltage across the capacitors is given by

$$V_{C1} = \frac{T_1}{T_1 - T_0} V_{in} \quad ; \quad V_{C2} = \frac{T_0}{T_1 - T_0} V_{in} \quad (5)$$

From (2), (4) and (5), the peak dc-link voltage across the diode and inverter bridge is

$$v_{dc} = V_{C1} + V_{C2} = \frac{T}{T_1 - T_0} V_{in} = BV_{in} \quad (6)$$

The average current of the inductors and capacitors can be calculated by the system power rating, $P$

$$I_{L1} = I_{L2} = I_{in} = P / V_{in} \quad (7)$$

$$I_{C1} = I_{C2} = I_{dc} - I_{L1} \quad ; \quad I_D = 2I_{L1} - I_{dc} \tag{8}$$

Also, $T = T_0 + T_1$, $D = T_0/T$, $B = 1/(1-2D)$, $D \leq 1 - M$

where, $T_0$ - interval of shoot through state, $T_1$ - interval of non-shoot through state, $B$ – Boost factor, $M$ –Modulation Index

## III. CIRCUIT ANALYSIS OF SWITCHED INDUCTOR Z SOURCE SINGLE PHASE INVERTER

Switched Inductor (SL) Z source single phase inverter shown in Fig. 2 has the combination of $L_1$–$L_3$–$D_1$–$D_3$–$D_5$ and $L_2$–$L_4$–$D_2$–$D_4$–$D_6$ to perform the functions of top and bottom SL cells respectively. Both SL cells are used to store and transfer the energy from the capacitors to the dc bus under the switching action of the main circuit.[5]

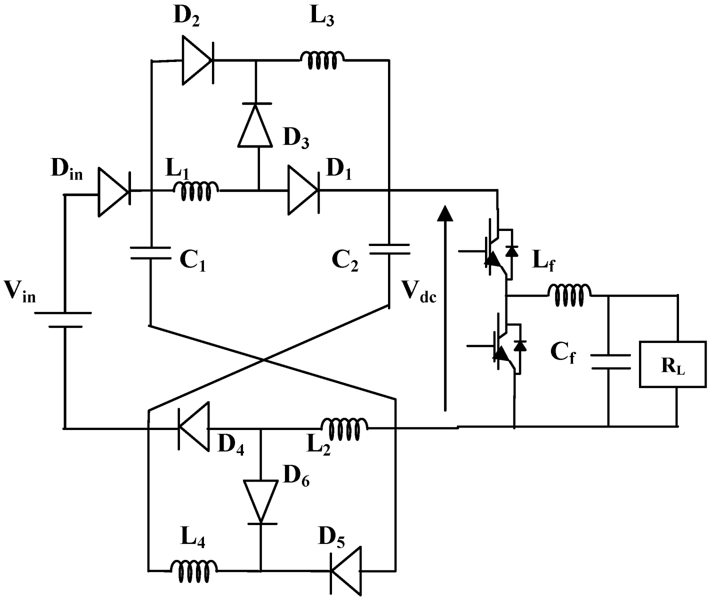


Fig. 2. Switched Inductor Z source single phase inverter

During the shoot through state, $D_1$ and $D_2$ are ON, and $D_3$ is OFF in the top SL cell, so $L_1$ and $L_3$ are charged by $C_1$ in parallel. For the bottom SL cell, $D_4$ and $D_5$ are ON, and $D_6$ is OFF. $L_2$ and $L_4$ are charged by $C_2$ in parallel.

In non – shoot through state, $D_1$ and $D_3$ are OFF, and $D_5$ is ON in the top SL cell, so $L_1$ and $L_2$ are connected in series. For the bottom SL cell, $D_4$ and $D_5$ are OFF, and $D_5$ is ON. $L_3$ and $L_4$ are connected in series, and the stored energy is transferred to the main circuit and

$$V_{C1} = V_{C2} = V_C \tag{9}$$

The inductor current $i_{L1}$ increases during switching ON and decreases during switching OFF. During switching ON, the corresponding voltage across $L_1$, $V_{L1\text{-ON}}$ is $V_C$ .

Applying the volt–second balance principle to $L_1$, voltage across $L_1$ during switching OFF is given by

$$V_{L1-OFF} = -\frac{D}{1-D} V_C = V_{L3-OFF} \tag{10}$$

The inductor current $i_{L3}$ increases during switching ON and decreases during switching OFF. The corresponding voltages across $L_3$ are equal to $V_{C1}$ and $-(V_{C2} - V_{in} + V_{L1\text{-OFF}})$.

Applying the volt–second balance principle to $L_3$

$$DTV_{in} = (1-D)\,T\,\left(V_C - V_{in} - \frac{D}{1-D} V_C\right) \tag{11}$$

$$V_C = \frac{1-D}{1-3D} V_{in} \tag{12}$$

During switching OFF, $C_1$, $L_1$, $L_3$, and the voltage source $V_{dc}$ form a close loop; so

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

$$V_{dc} = \frac{1+D}{1-3D} V_{in} = B V_{in} \tag{13}$$

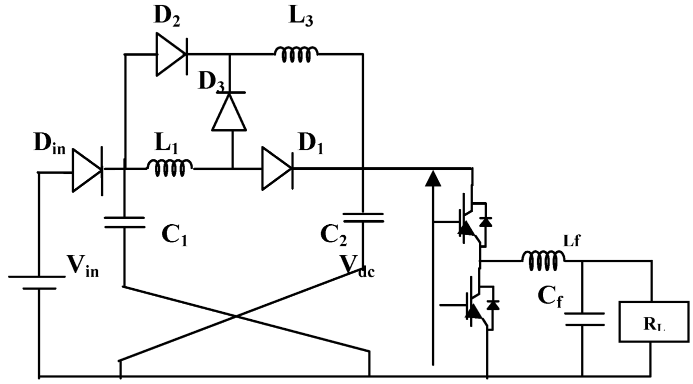


Fig. 3. Semi Switched Inductor Z source single phase inverter

Fig. 3 shows semi switched inductor Z source single phase inverter which can be formed either with upper or lower switched inductor cells to provide additional voltage boosting with reduced passive elements. This inverter circuit is constructed with upper SL cell.

## IV. CIRCUIT ANALYSIS OF SWITCHED INDUCTOR QUASI Z SOURCE SINGLE PHASE INVERTER

SL quasi ZSI consists of three inductors ($L_1$, $L_2$, and $L_3$), two capacitors ($C_1$ and $C_2$), and four diodes ($D_{in}$ , $D_1$ , $D_2$ , and $D_3$). The combination $L_2$–$L_3$–$D_1$–$D_2$–$D_3$ acts as a switched-inductor cell.

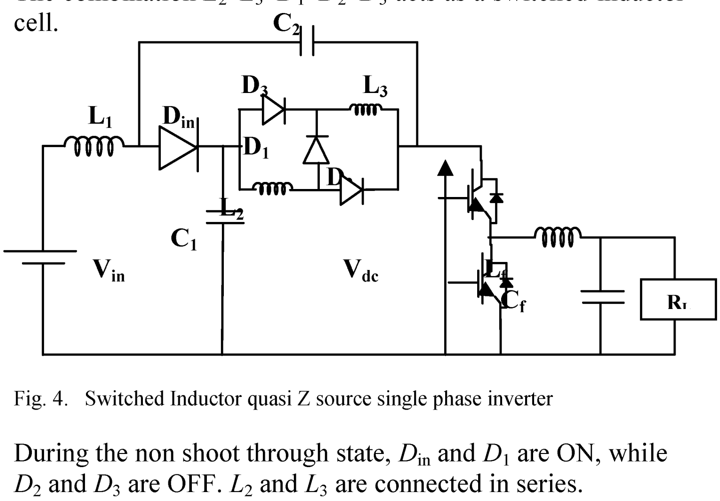


Fig. 4. Switched Inductor quasi Z source single phase inverter

During the non shoot through state, $D_{in}$ and $D_1$ are ON, while $D_2$ and $D_3$ are OFF. $L_2$ and $L_3$ are connected in series.

The capacitors $C_1$ and $C_2$ are charged, while the inductors $L_1$, $L_2$, and $L_3$ transfer energy from the dc voltage source to the main circuit. The corresponding voltages across $L_2$ and $L_3$ in this state are $V_{L2\_non}$ and $V_{L3\_non}$ respectively.

$$\begin{aligned} V_{L1} &= V_{C1} - V_{in} \\ V_{L2} &= V_{L2\_non} = V_{C2} - V_{L3\_non} \\ V_{L3} &= V_{L3\_non} = V_{C2} - V_{L2\_non} \\ V_{dc} &= V_{C1} + V_{C2} \end{aligned} \tag{14}$$

During the shoot-through state, $D_{in}$ and $D_1$ are OFF, while $D_2$ and $D_3$ are ON. $L_2$ and $L_3$ are connected in parallel. The capacitors $C_1$ and $C_2$ are discharged, while inductors $L_1$, $L2$, and $L_3$ store energy, hence

$$\begin{aligned} V_{L1} &= -V_{C2} - V_{in} \\ V_{L2} &= V_{L3} = -V_{C1} \end{aligned} \tag{15}$$

Applying the volt-second balance principle to $L_2$ and$L_3$ from (14) and (15),

$$V_{L2\_non} = V_{L3\_non} = -\frac{D}{(1-D)} \; V_{C1} + V_{C2}$$

$$V_{C2} = \frac{2D}{(1-D)} \; V_{C1} \tag{16}$$

Applying the volt-second balance principle to $L_1$ from (14), (15) and (16),

$$\begin{aligned} V_{C1} &= \frac{(1-D)}{(1-2D-D^2)} V_{in} \\ V_{C2} &= \frac{2D}{(1-2D-D^2)} V_{in} \end{aligned} \tag{17}$$

The peak dc-link voltage cross the inverter main circuit is expressed
as

$$V_{dc} = V_{C1} + V_{C2} = \frac{(1+D)}{(1-2D-D^2)} \; V_{in} \tag{18}$$

## V. SIMULATION RESULTS AND DISCUSSIONS

Simulation studies are performed on the open-loop configuration of all proposed topologies in MATLAB/Simulink. Two IGBT switches with anti parallel diode connected in a single leg act as half bridge inverter. The IGBT parameters are: internal resistance, $R_{on}$ = 1m Ω and snubber resistance, $R_s$ = 0.1MΩ. Discrete PWM generator is used to generate pulses for carrier-based PWM (Pulse Width Modulation) Table I provides a list of the simulation parameters for the proposed inverters.

In all the topologies, input voltage is kept constant at 150 V and a load of 15 Ω resistor is used. All dc-side capacitors are 1000 µF and inductors are 5 mH. The ac-side second order filter of 900 µF capacitor and 15 mH inductor is used. The voltage boost performances of various proposed topologies are given in Table II. Topologies shown in Fig. 1 to 4 exhibit higher voltage boost when compared with traditional and Z source single phase inverters. All simulation results comply with the equations derived in Section II to IV.

TABLE I. SIMULATION PARAMETERS

| | | |
|---|---|---|
| Input dc voltage | | 150V |
| Z source Network | L | 5mH |
| | C | 1000µF |
| Output Filter | Lf | 15mH |
| | Cf | 9000µF |
| Carrier frequency, fc | | 1080Hz |
| Modulation index, M | | 1.0 |
| Resistive load RL | | 15Ω |
| Frequency of output voltage | | 50Hz |

TABLE II. SIMULATED RESULTS OF VOLTAGE BOOST PERFORMANCE OF VARIOUS PROPOSED TOPOLOGIES

| Sl. No. | Topology | Current (In Amps) | | Voltage (In Volts) | |
|---|---|---|---|---|---|
| | | $I_{load}$ | %THD | $V_{Inv}$ | %THD |
| 1 | Half Bridge Inverter | 10.88 | 0.24 | 163.2 | 0.24 |
| 2 | Z Source Half Bridge Inverter | 6.59 | 1.29 | 98.87 | 1.29 |
| 3 | Quasi Z source single phase Inverter | 14.2 | 1.82 | 213.1 | 1.82 |
| 4 | Switched Inductor Z source single phase Inverter | 15.51 | 2.58 | 232.7 | 2.58 |
| 5 | Semi Switched Inductor Z source single phase Inverter | 17.39 | 5.86 | 260.9 | 5.86 |
| 6 | Switched Inductor Quasi Z source single phase Inverter | 14.48 | 2.24 | 217.2 | 2.24 |

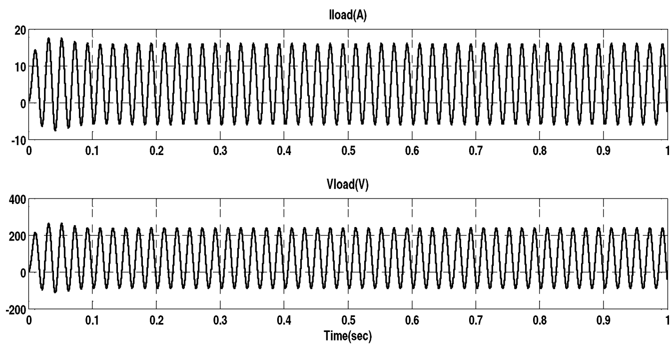


Fig. 5. Load current and voltage waveforms of half bridge inverter

Figs. 7 to 10 show the simulation results corresponding to topologies shown in Figs. 1 to 4, which are for the proposed quasi, switched inductor, semi switched and switched inductor quasi Z source single phase inverter topologies, where they are operated with modulation index of 1.0 to achieve a higher voltage boost. Voltage stress across the capacitors and current through the inductors for the discussed topologies are presented in the Figs.11 – 15.

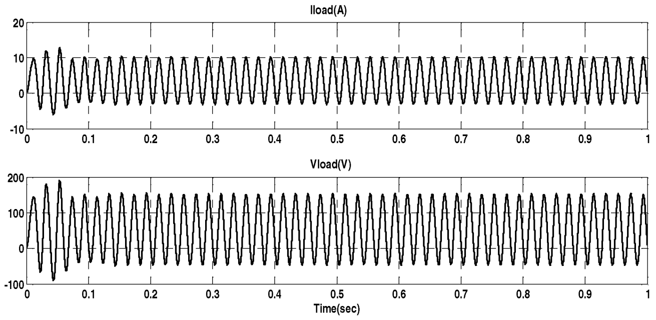


Fig. 6. Load current and voltage waveforms of Z source half bridge inverter

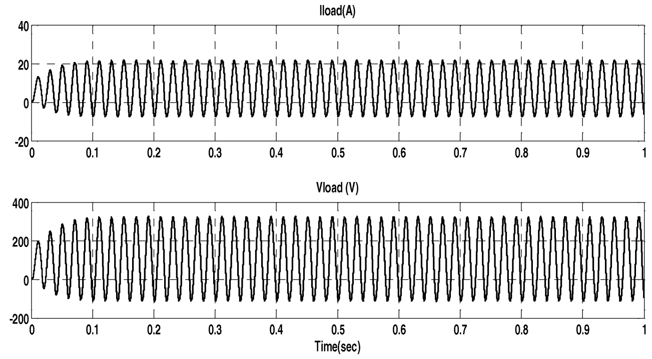


Fig. 7. Load current and voltage waveforms of quasi Z source single phase inverter

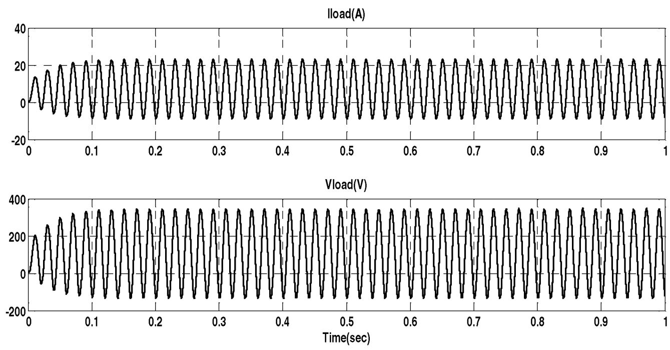


Fig. 8. Load current and voltage waveforms of Switched inductor Z source single phase inverter

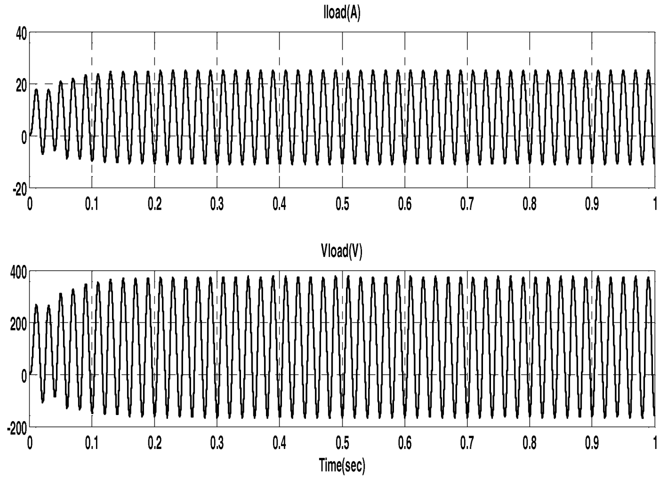


Fig. 9. Load current and voltage waveforms of semi switched inductor Z source single phase inverter

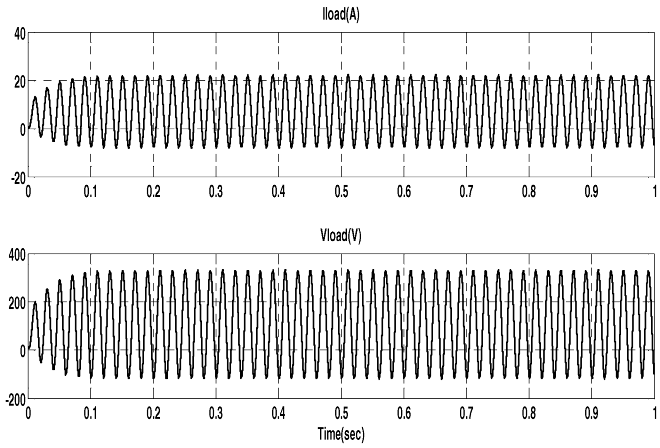


Fig. 10. Load current and voltage waveforms of switched inductor quasi Z source single phase inverter

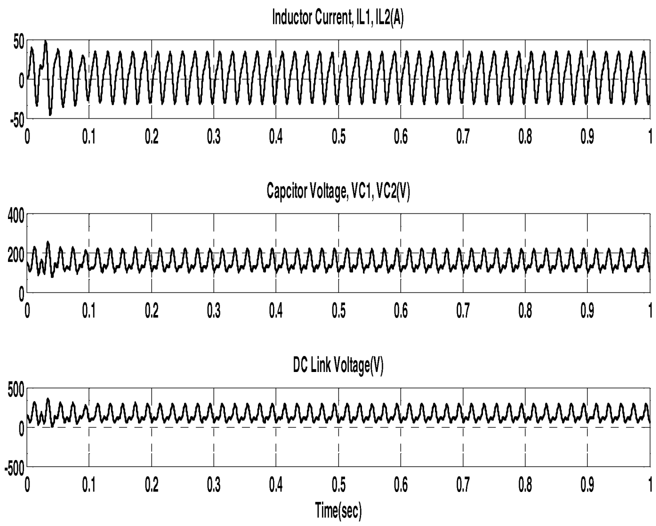


Fig. 11. Inductor current, capacitor voltage, DC link voltage waveforms of Z source single phase inverter

It is found that inductor current $I_{L1} = I_{L2}$ and capacitor voltage $V_{C1} = V_{C2}$ for Z source half bridge inverter.

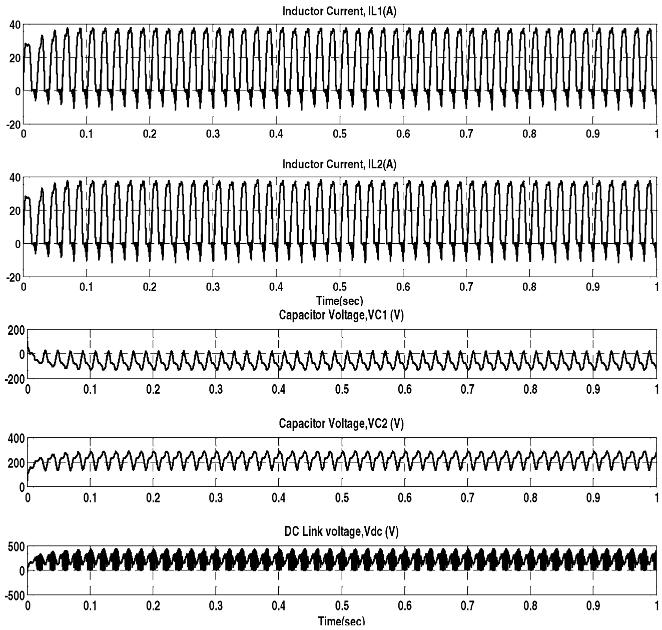


Fig. 12. Inductor current, capacitor voltage, DC link voltage waveforms of quasi Z source single phase inverter

Inductor current $I_{L1} = I_{L2}$ and capacitor voltage $V_{C1}$ # $V_{C2}$ for quasi Z source single phase inverter. Also the voltage on capacitor $C_1$ is greatly reduced, which requires lower capacitor rating. In the above figure12 inductor current, capacitor voltage and DC link voltage waveforms for quasi Z source single phase inverter are shown, whose values are found to be uniform and produce continuous current and regulated voltage to the inverter.

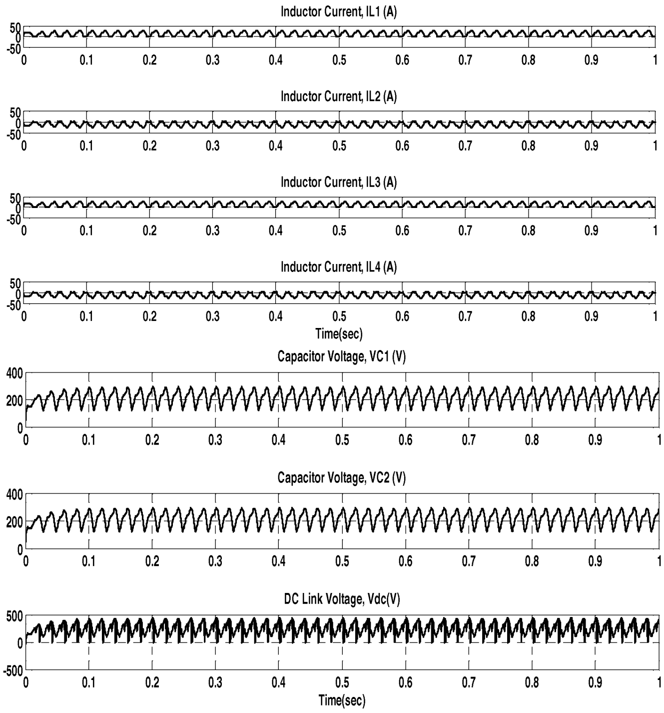


Fig. 13. Inductor currents, capacitor voltages, DC link voltage waveforms of switched inductor Z source single phase inverter

It can be observed that all the inductor currents $I_{L1}$, $I_{L2}$, $I_{L3}$and $I_{L4}$ are equal and capacitor voltage $V_{C1} = V_{C2}$ for switched inductor Z source single phase inverter.

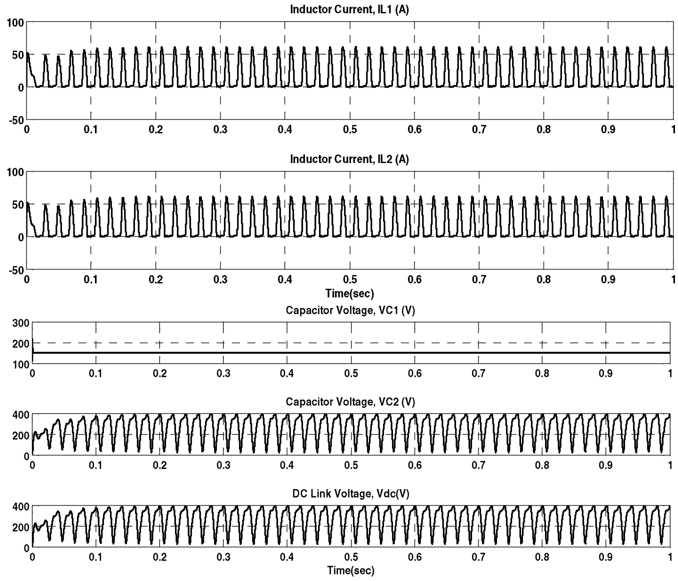


Fig. 14. Inductor currents, capacitor voltages, DC link voltage waveforms of semi switched inductor Z source single phase inverter

It is found that inductor current $I_{L1} = I_{L2}$ and capacitor voltage $VC_1$ # $VC_2$ for semi switched Z source single phase inverter.

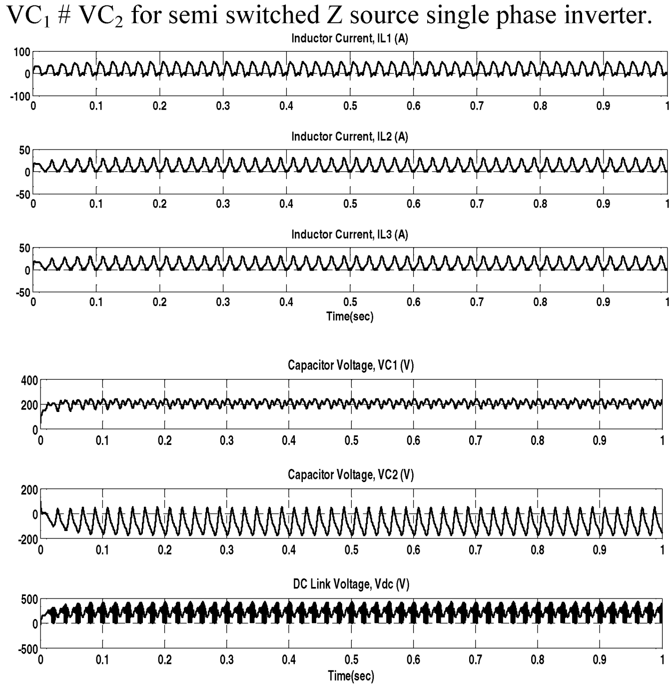


Fig. 15. Inductor currents, capacitor voltages, DC link voltage waveforms of switched inductor quasi Z source single phase inverter

Inductor currents, $IL_1$ and $IL_2$ are divided equally and the capacitor voltages, $VC_1$ and $VC_2$ are equal in the switched inductor quasi Z source single phase inverter

## VI. CONCLUSIONS

This paper has proposed a new family of single phase Z source inverters and implemented using different types of impedance networks with the following main characteristics: high boost voltage inversion ability, continuous input current and reduced voltage stress on capacitors and lower current stress on inductors. The proposed inverters are applicable for photovoltaic applications, where a low input voltage is inverted to a high ac output voltage.

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