Switched Inductor Z Source Inverters for High Boost Applications

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***Abstract*—This paper analyses a different configuration for the classical Z-Source Inverters (ZSI) which is named as Switched Inductor Z-Source Inverters (SL-ZSI) through simulation results. This configuration uses a unique impedance network that helps in the voltage adjustability. Comparing with the ordinary Z-source inverter, the new configuration provides more voltage inversion ability and enhances the output power quality of the main circuit considerably. The various applications of this configuration include DC-AC, AC-AC, DC-DC and AC-DC power conversions.**

***Index Terms*—Inverter, voltage source inverter (VSI), Z-source inverter (ZSI), switched inductor Z-source inverter (SI-ZSI)**

I. INTRODUCTION

Traditionally the inverters are divided into Voltage Source Inverters (VSI) and Current Source Inverters (CSI). But they have some conceptual and theoretical barriers and limitations. The VSI and CSI are either a boost or a buck converter and cannot be a buck–boost converter. Their obtainable output voltage range is limited to either greater or smaller than the input. Their main circuits cannot be interchangeable. In other words, neither the VSI's main circuit can be used for the CSI's, nor vice versa. Lastly they are vulnerable to EMI noise in terms of reliability. The problem with EMI noise is that it results in the switching ON of switches in the same leg which results in dead short circuit across the source. The switching ON of switches in the same leg of a traditional inverter is a forbidden condition in the switching states of the inverter.Fig.1 shows a three-phase VSI [3].

The switches in the same leg have to work complimentary. The forbidden state in which the switches in the same leg work together is called shoot through state. As a solution to all these problems a new configuration called Z source inverters are proposed which converts the disadvantageous shoot through state into its advantage [2].

In the sections following, the working and problems associated with the classic ZSI will be discussed and in the later sections the new configuration will be introduced. Then various modes of operation of the SL-ZSI will be discussed, followed by the mathematical analysis of the topology to find the boost and inversion ability of the new topology and at last simulation results are used to validate it.

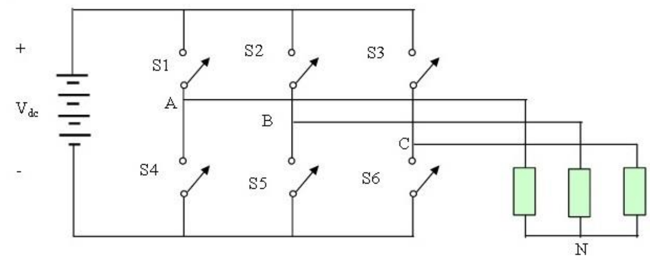

Fig.1. Three phase Voltage source inverter

II. Z SOURCE INVERTERS

The Z source inverter employs a unique impedance network to couple the inverter main circuit to the dc power supply. This two-port impedance network consist of a split-inductor L_1 and L_2 and capacitors C_1 and C_2 connected in X shape. The Z-source inverter utilizes the shoot-through state to boost the DC bus voltage by gating on both the upper and lower switches of a phase leg. Fig.2 shows a Z source network [2].

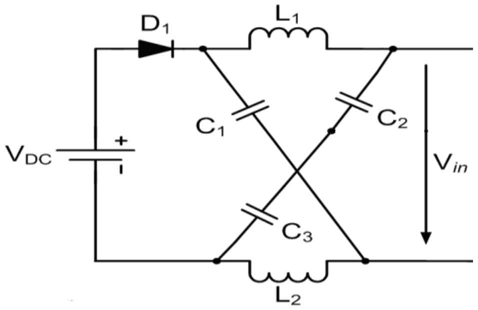

Fig.2 Z source network

A. Drawbacks of Z- Source Inverters

The Boost ability of the ZSI is very much controlled by the shoot through duty ratio (D) that we provide. In order to provide a very high boost factor for low voltage DC energy source it needs to work with large D. That is the ZSI needs to work in the extreme condition of long shoot through zero state. As a result, the modulation index (M) of the circuit is decreased to a very small value. It is important to note that the inversion ability of the inverter very much depends upon the modulation index. Ultimately the power quality and inversion ability of the system is very much disturbed by the low M and high D value.

For fuel cells, batteries and photovoltaic cells we need an upgraded and enhanced configuration for the conventional Z source which can provide very high boost with low D value and high M value [5]. A solution for this problem is the new switched inductor Z-source inverters.

III. SWITCHED-INDUCTOR Z SOURCE INVERTERS

The switched-inductor Z-source inverter (SL-ZSI) is considered as a modification of the classical ZSI. This class of ZSI can provide very high boost with a very minimum value of shoot through and hence the problem of low modulation index and the related problems of reduced power quality and inversion ability can be avoided. This topology is totally different from any other existing Z-source inverters from the viewpoint of circuit structures and operation principles. The new configuration has retained the X structure of the classic ZSI and in addition added six more diodes and two extra inductors.

The new structure is extensible for the further development using the coupled inductor techniques and other potential improving techniques. The modulation techniques that can be applied to the classical ZSI are also applicable to the new configuration.

A. Operation principle

Fig. 3 shows a SL- Z-source inverter [1]

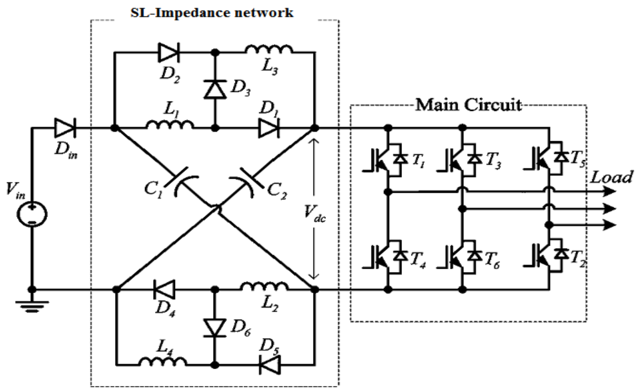

Fig.3 Switched Inductor Z source inverter

From the viewpoint of the switching states of the main circuit connected with SL impedance network, the operation principles of the new impedance network are similar to those of the classical Z-source impedance network. Assume that at $t=0^-$ sec we had an active state. Now at t= 0 sec our capacitors are charged .Thus the voltage across the two capacitors will add up to a value greater than the input voltage thus the diode at the front end is reverse biased as shown in the Fig.4 which is the equivalent circuit during the shoot through state[1]

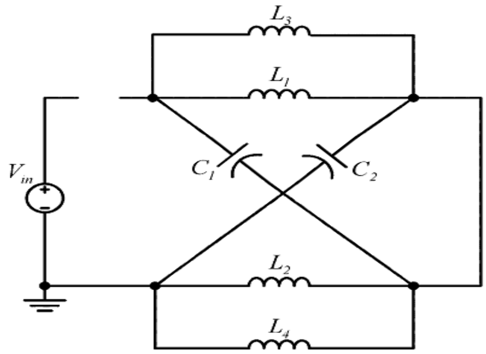

Fig.4 Equivalent circuit during Shoot through

For the top switched inductor cell, D_1 and D_2 are ON, and D_3 is OFF. L_1 and L_3 are charged by C_1 in parallel. For the bottom switched inductor 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. SL cells perform the same function to absorb the energy stored in the capacitors.

After the shoot through, the inductors are in charged condition and the capacitors are in discharged condition. Now the non shoot through mode happens. This mode corresponds to the six active states and two zero states of the main circuit and the equivalent circuit is shown in Fig. 5[1]. In this mode the diode D_{in} at the front end is forward biased and for the top switched inductor cell, D_1 and D_3 are OFF, and D_5 is ON. L_1 and L_2 are connected in series, and the stored energy is transferred to the main circuit. For the bottom switched inductor 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. At the same moment, to supplement the consumed energy of C_1 and C_2 during the shoot-through state, C_1 is charged by V_{in} through the bottom switched inductor cell, and C_2 is charged by V_{in} via the top switched inductor cell [1].

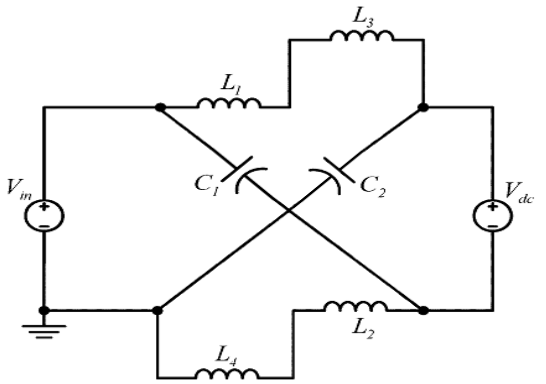

Fig 5 Equivalent circuit during the non shoot-through states

From the operation principle, it is quite evident that the inductors are being charged parallel during the shoot through state by the capacitors. Later during the active states, the inductors are discharged as in series. Thus the load receives power from the source as well as from the stored energy in the inductors, thus providing a boosted output at the load end. The switching between the parallel and series configuration of the inductors is one of the unique characteristics of SL-ZSI.

B. Mathematical analysis of SL- Z-source inverter

For mathematical analysis, assume all the inductors and capacitors to have the same inductance (L) and capacitance (C), respectively. In the steady state, we have

$$V_{c1} = V_{c2} = V_c \quad (1)$$

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 equal to V_C . Applying the volt–second balance principle to L_1 , we can get the corresponding voltage across L_1 during switching OFF, $V_{L1\text{- OFF}}$, which is expressed by

$$v_{L1-off} = \frac{D}{1-D} = v_{L3-off} \quad (2)$$

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 ,we have

$$DT\, V_{C1} = (1 - D)T\, (V_{C2} - V_{in} + V_{L1\text{- OFF}}) \quad (3)$$

or $$DT\, V_{in} = (1 - D)T(V_C - V_{in} - D_1 - D\, V_C) \quad (4)$$

Hence

$$v_c = \frac{1-D}{1-3D} v_{in} = v_{c1} = v_{c2} \quad (5)$$

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

$$V_C = V_{dc} + V_{L1\text{- OFF}} + V_{L3\text{- OFF}} \quad (6)$$

Therefore

$$v_{dc} = \frac{1+D}{1-3D} v_{in} = Bv_{in} \quad (7)$$

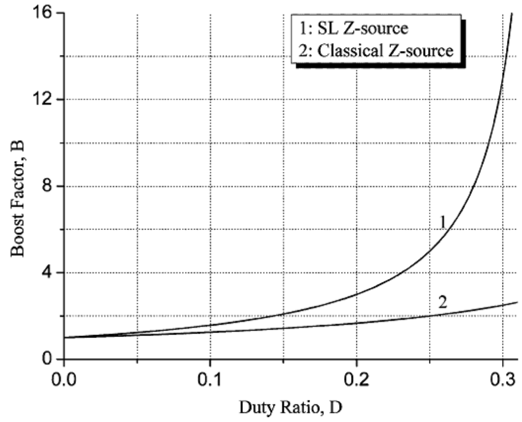

Fig.6 Boost ability comparison of the classical Z-source impedance network and the proposed SL Z-source impedance network

For the comparison of the individual boost ability, the curves of the boost factor B versus the duty ratio D for classical Z-source impedance network and the new SL Z-source impedance network, respectively, are shown in Fig.6. The boost ability of the new SL impedance network is significantly increased compared with that of the classical Z-source impendence network.

The boost inversion ability of a whole Z-source is determined by the interactions of Z-source impedance and the PWM control method applied to the main circuit. The PWM control method called simple boost is been applied here. In simple boost method the obtainable duty ratio of the shoot-through state can be regarded as a constant value, and its maximum value is limited to (1 − M) as given in [2]. The voltage conversion ratio of the whole inverter G can be expressed by

$$G = \frac{v_{pn}}{\frac{v_{in}}{2}} = MB \quad (8)$$

where v_{pn} is the peak value of the output phase voltage. The maximum voltage con-version ratio G_{max} versus any desired modulation index M can be expressed by

$$G = MB\,|_{D=1-M} = \frac{M(2-M)}{3M-1} \geq G_{0-s} \quad (9)$$

where $G_{0\text{-s}}$ is defined as the maximum voltage conversion ratio of the classical Z-source inverter and its expression depends on M, given by

$$G_{0-s} = \frac{M}{2M-1} \quad (10)$$

The shoot-through duty cycle varies in each cycle. The average duty ratio of the shoot-through zero state, D' is expressed by

$$D' = \frac{T_0}{T} = \frac{2p - 3\sqrt{3}M}{2p} \qquad (11)$$

Substituting (11) in B we get the equivalent boost factor B' under the condition of variable duty ratios

$$B' = \frac{1 + D'}{1 - 3D'} = \frac{4p - 3\sqrt{3}M}{9\sqrt{3}M - 4p} \qquad (12)$$

Therefore, the maximum voltage conversion ratio G_{max} versus any desired modulation index M approximates to

$$G = \frac{v_{pn}}{\frac{v_{in}}{2}} = MB = \frac{4p - 3\sqrt{3}M}{9\sqrt{3}M - 4p} > G_{o-m} \qquad (13)$$

where G_{0-m} is defined as the maximum voltage conversion ratio of the classical Z-source inverter and its expression depends on M, given by

$$G_{o-m} = \frac{pM}{3\sqrt{3}M - p} \qquad (14)$$

Fig.7 shows the maximum voltage conversion ratios of the proposed inverter under the simple boost control condition where curve 1 and curve 2 correspond to the proposed SL Z-source inverter and the classical Z-source inverter, respectively. It is shown that the voltage boost ability is unavailable at M = 1. However, if M<1, with the decreasing of M, the voltage boost inversion ability of the proposed inverter becomes much stronger than that of the classical Z-source inverter. It means that for a given voltage conversion ratio, a higher modulation index can be used in the proposed inverter to improve the inverter output performance.

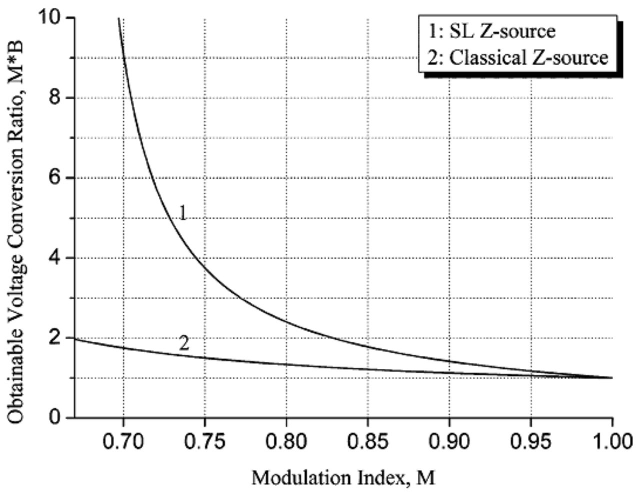

Fig.7 Maximum voltage conversion ratios of the proposed inverter under the simple boost control condition

C. Modulation technique for SL Z source inverter

In this project simple boost sine PWM is applied for the switching of the proposed inverter. Fig 6 shows the control scheme [3].

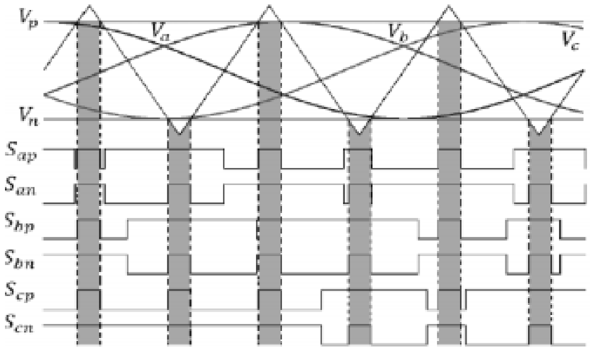

Fig.8 Simple boost control (SBC)

In SBC, there are five modulation curves: two shoot through envelop signal V_p and V_n and three modulating reference sinusoidal signal V_a , V_b and V_c. The amplitude of shoot through (ST) envelop signal should be greater than or equal to peak value of modulating sinusoidal reference signal. By comparing DC signal with the high frequency triangular carrier, shoot through switching pulses are generated. The three-phase modulating reference signals are compared with high frequency triangular signal to produce the switching pulses. These two signals are compared by a comparator. Therefore when triangular signal is greater than upper envelope V_p or less than lower envelope V_n, the circuit enters into shoot-through (ST) state. The waveforms for simple boost control are given in Fig.8 by logical OR gate shoot-through states are inserted into switching waveform. These pulses are sent to the gate of the switching devices in the inverter. For SBC the modulation index (M) increases with the decrease in the shoot through duty ratio (D_o).

IV. SIMULATION RESULTS

To verify the theoretical results, a simulation example for the voltage inversion from DC 36 V to AC 198 V (rms) is performed in the MATLAB/Simulink software environment. The main circuit parameters are chosen as follows:

1) SL Z-source impedance network: $L_1 = L_2 = L_3 = L_4 = 1$ mH, $C_1 = C_2 = 800$ μF
2) Three-phase output filter: $L_f = 1$ mH, $C_f = 22$ μF;
3) Switching frequency $f_s = 1/T = 10$ kHz;
4) Three-phase balanced RL load, R = 10 Ω, L= 15 mH;
5) All components are assumed ideal.

A. Three-phase SL Z-Source Inverter simulation results

For the three-phase SL ZSI, with an input DC voltage V_{in}=36 V, shoot-through duty ratio D=0.3 and M=0.7, then the expected boost ratio B is 13 and the overall inverter boost G is 9. It means the output must be nine times the input voltage. Fig.9 shows the output voltage waveform. From the simulation results, it is seen that the output line-to-line voltage

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is around 280V (peak) and the RMS voltage is found out as 198V.

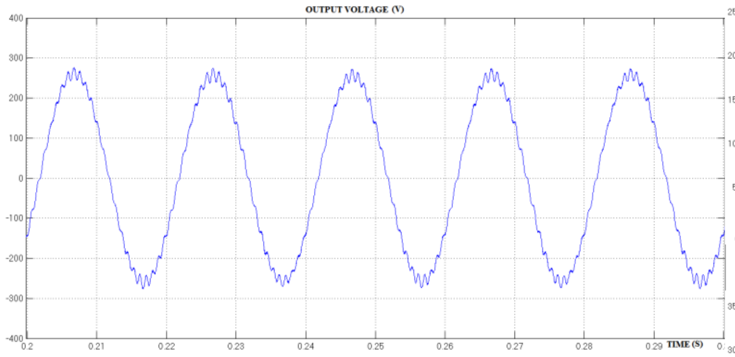

Fig.9 Output Voltage

The output current is found out to be having a peak value of 14 A. Fig 10 shows the output current waveform.

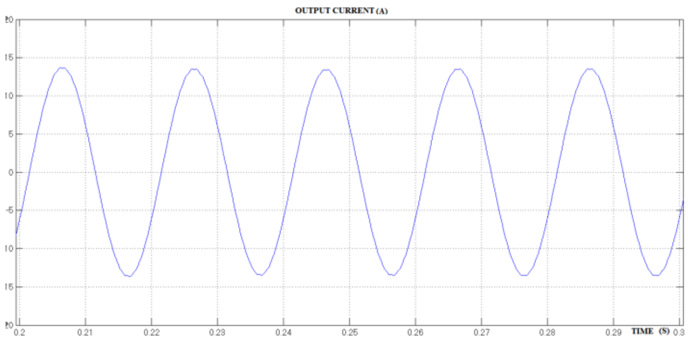

Fig.10 Output Current

With input DC voltage of V_{in}=36V, the DC link voltage V_{dc} is expected to be equal to 468V which is 13 times the input DC voltage. The simulation result is shown in Fig.11.

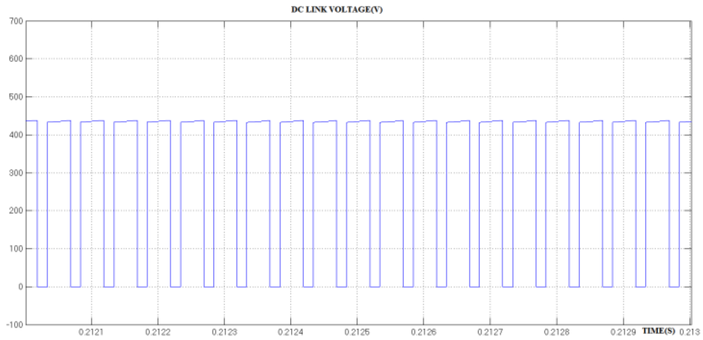

Fig.11 Dc link voltage

The capacitor voltages C_1 and C_2 are supposed to be of equal value and they should together contribute for the DC link voltage which means each capacitor should have a voltage equal to 240V. Fig.12 and Fig.13 represent the capacitor voltages of C_1 and C_2 respectively

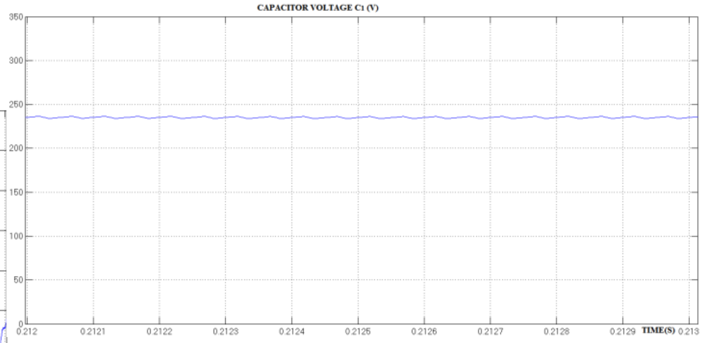

Fig.13 Capacitor Voltage (C_1)

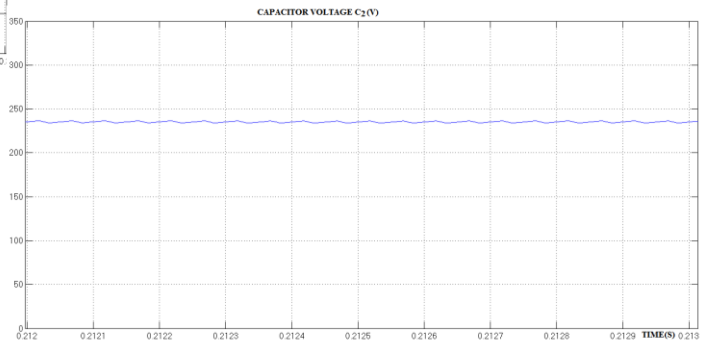

Fig.13 Capacitor Voltage (C_2)

The simulation result in Fig. 14 shows the inductor current.

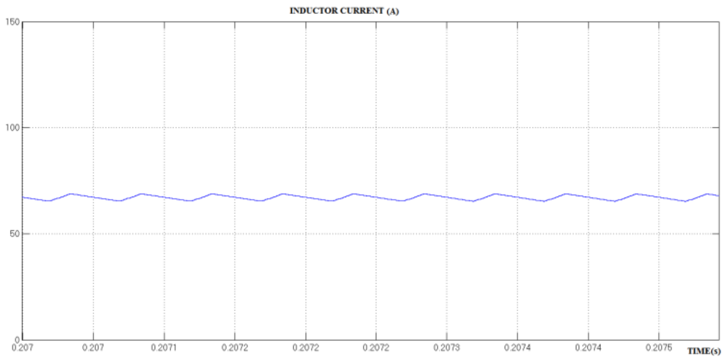

Fig.14 Inductor current

B. Single-phase SL Z-Source Inverter simulation results

For a single-phase SL ZSI with an input DC voltage of 3.5V, the simulation result shows an output AC voltage of 15V (peak). This means that in single-phase inverter, the overall inverter boost G has reduced to 4.2 from 9 in the three-phase inverter. Fig.15 shows the output voltage waveform.

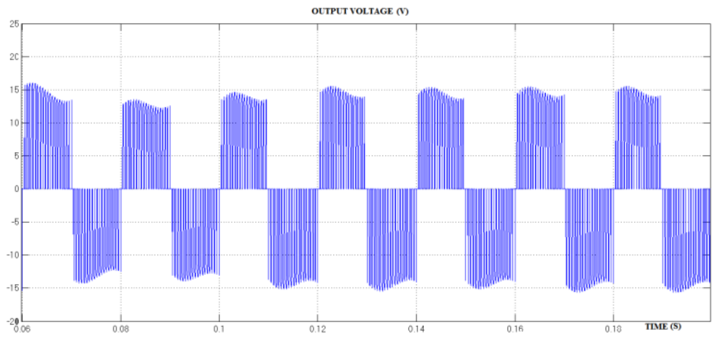

Fig. 15 output voltage waveform

Fig.16 shows the simulation result for the output current. It can be seen that the output current is 0.7 A(peak).

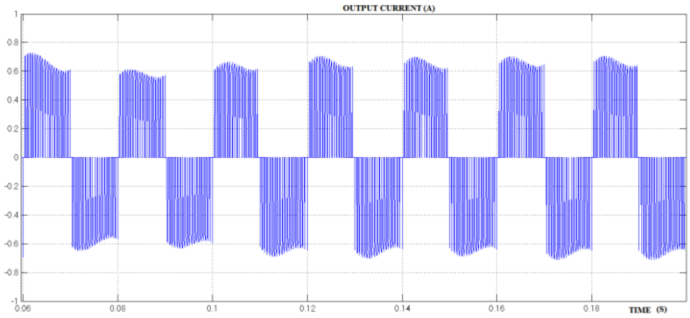

Fig.16 Output current

For the single-phase SL ZSI, the DC link voltage is shown in Fig.17. The DC link voltage is found out to be 15 V. In a three-phase inverter, the theoretical boost for the DC link is thirteen times the input voltage. But, for a single phase inverter, it is seen that the boost factor B is only 4.2.

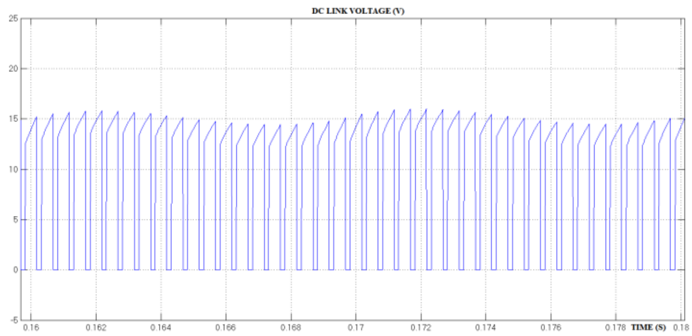

Fig.17 DC link voltage

Fig.18 and Fig.19 shows the simulation results for the capacitor voltages across C_1 and C_2 respectively.

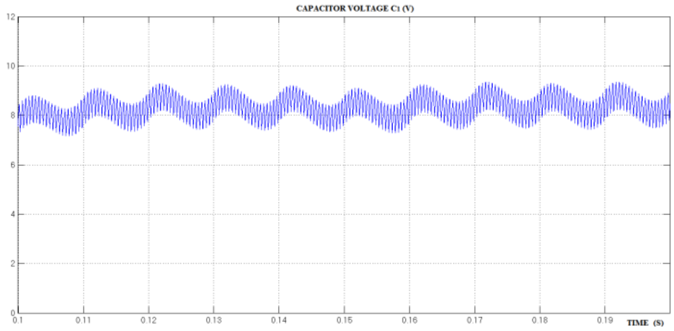

Fig.18 capacitor voltage (C_1)

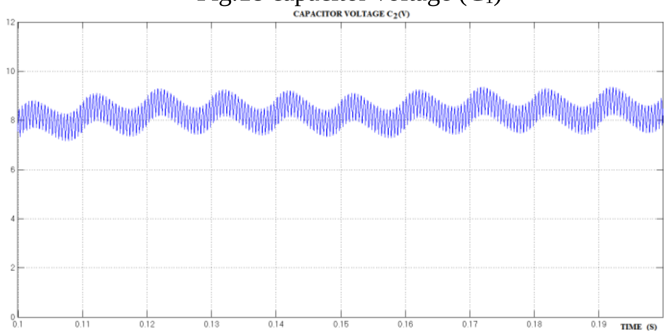

Fig.19 capacitor voltage (C_2)

It is seen that the capacitor voltage waveforms are identical in nature.

V.CONCLUSION

This paper analyses an improvised configuration for classical Z-source inverters through simulation results. This inverter uses a unique SL Z-source impedance network to couple the low dc voltage energy source to the main. The ability of the inductor configuration to switch between parallel and series connection during the shoot through and active state allows this topology to provide very high boost as compared with the classical Z-source inverter. The high boost and inversion ability of this topology was analyzed through simulation results in MATLAB/Simulink for three-phase and single-phase SL Z source inverters. Single-phase SL Z-source inverter is not found to be effective as three-phase SL S-source inverter. In single phase SL ZSI, the theoretical boost and inversion abilities is almost reduced by half. Hence, it is concluded that the new SL-Z source inverter is more effective in three-phase circuits as compared to the single phase circuits.

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