COMPARATIVE STUDY OF Z-SOURCE TOPOLOGIES WITH VARYING MODULATION INDEX

Pardeshi Mayur Mahendra[1], Prof. M. F. A. R Satarkar[2]
[1]M.Tech in Power System, [2]Professor
Dr. BATU, Lonere, Dept. of Electrical Engg. Dr. BATU, Lonere

Abstract
A comparative study of Z-Source topologies are compared with each other and presented in this paper. Z-source has buck-boost ability and uses shoot through state which buck-boost the output of the inverter and also increase the reliability of the converter and extend its application in power generation technologies. To overcome the drawback of Z-Source there are many modifications done in structure and are presented in this paper. The Sine PWM technique is use as a control technique for the inverter. The selection of high modulation index can reduce the inverter's dc link voltage overshoot and increasing power delivery capacity of the inverter. This paper presents the boost output capability of modifying topology of z-source and shows the buck-boost operation of Z-source topologies with the change in modulation index and compares them with each other. These comparisons are made with the help of MATLAB-Simulink and are presented with simulation results.

Index Terms: Buck-Boost, Modulation Index, Z-Source Inverter.

I. INTRODUCTION

One of the most promising power electronics converting topologies is the Z-source inverter (ZSI). The ZSI is an emerging topology for power electronics dc–ac converters with interesting properties such as buck-boost characteristics and single stage conversion. A two-port network, composed of two capacitors and two inductors connected in an X shape, is employed to provide an impedance source (Z-source) network, coupling the inverter main circuit to the dc input source. The capacitor and inductor are energy storage devices. The capacitor resists a change in voltage and it is used to reduce the voltage sag or voltage swell (provides constant voltage). The inductor resists a change in current and it is used to reduce the ripple in output current of converter (provides constant current). The ZSI advantageously uses the shoot through (ST) state to boost the input voltage, which improves the inverter reliability and enlarges its application fields like in renewable energy power generation systems and electric drive speed control. In comparison with other power electronics converters, it provides an attractive single stage dc–ac conversion with buck-boost capability with reduced cost, reduced volume, and higher efficiency due to a lower component number. For emerging power-generation technologies, such as fuel cells, photovoltaic (PV) arrays, and wind turbines, and new power electronic applications such as electric and hybrid vehicles, the ZSI is a very promising and competitive topology.

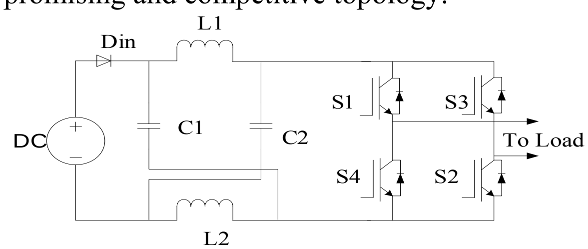

Fig. 1: Equivalent circuit of Single-Phase ZSI.

In addition, it can be used as voltage or current fed ZSI for two-level or multilevel configuration. This paper focuses on the various topologies and their modifications of the two-level voltage-fed ZSI. The ZSI has some drawbacks that resulted in decreasing the converter efficiency, such as unidirectional power flow, light-load operation, high inrush current during starting, a discontinuous input current, higher Z-network capacitor voltage, isolated source, and inverter dc rail. To solve these drawbacks in basic ZSI topology, there have been many modifications in the structure. This report presents a review of the various topologies and there modifications.

II. Z-SOURCE INVERTER

To overcome the problems which is in VSI and CSI, the Z-Source Inverter is been implemented. Fig. 1 shows the comprehensive ZSI, where two capacitor and inductor are used. The inductor L_1 and L_2 and capacitors C_1 and C_2 connected in X shape is employed to deliver an impedance source coupled between the source and the inverter. The source may be battery, solar photovoltaic cell and fuel cell while the inverter may be single phase or three phase depending upon the type of load which may be single phase or three phase respectively.

A. Switching Stage

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 occurs only 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: 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, when the load terminal get shorted through both the upper and lower device of any one leg (either first or second) or get shorted by both of the 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.

The Z-source inverter has following drawbacks:

- No continuous input current.
- High start-up inrush current.
- Unidirectional power flow.
- Large voltage stress across the switches and capacitors.
- It is used for light load operation.

To overcome these above drawbacks of ZSI, there are many modification made in the configuration of ZSI.

III. SWITCHED INDUCTOR Z-SOURCE INVERTER

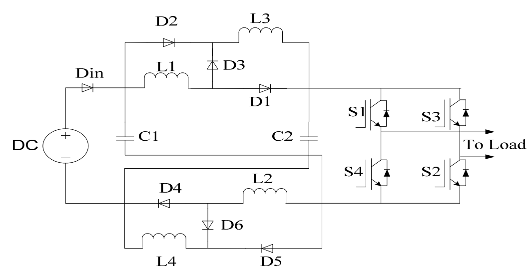

Fig. 2: Switched Inductor ZSI (SL-ZSI)

On the basis of the classical Z-source inverter, the developed impedance-type power inverter that is termed as switched inductor (SL) Z-source inverter. To enlarge voltage adjustability, the proposed inverter employs a unique SL impedance network to couple the main circuit and the power source. Compared with the classical Z-source inverter, the Switched Inductor Z-Source Inverter increases the voltage boost inversion ability significantly. Only a very short shoot-through zero state is required to obtain high voltage conversion ratios, which is beneficial for improving the output power quality of the main circuit. In addition, the voltage buck inversion ability is also provided in the Switched Inductor Z-Source Inverter for those applications that need low ac voltages.

Advantages of Switched Inductor ZSI (SL-ZSI).

- Achieve 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 startup, and the resulting voltage and current spike can destroy the devices.

To overcome the above drawback the new topology is proposed named Switch Inductor Quasi Z-Source Inverter.

IV. SWITCH INDUCTOR QUASI Z-SOURCE INVERTER

The design construction is quite change as compare to previous topologies. The SL-QZSI has three inductors (L_1, L_2 and L_3), two capacitors (C_1 and C_2) and three diodes (D_1,D_2 and D_3) which is shown in Fig. 3.

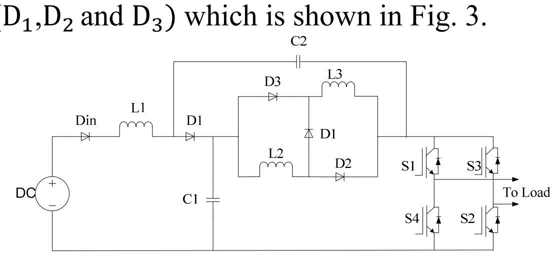

Fig. 3: Switched Inductor Quasi ZSI (SL-QZSI)

This topology deals with a new family of high boost voltage inverters called switched-inductor Quasi-Z-source inverters (SL-QZSIs). The SL-QZSI is based on the well-known QZSI topology and adds only one inductor and three diodes. In comparison to the SL-ZSI, for the same input and output voltages, the SL-QZSI provides continuous input current, a common ground with the dc source, reduced the passive component count, reduced voltage stress on capacitors, lower shoot-through current, and lower current stress on inductors and diodes. In addition, the proposed SL-QZSI can suppress inrush current at startup, which might destroy the devices.

Despite this increase in boost inversion, the SL-ZSI has several drawbacks: 1) it adds six diodes and two inductors, compared with the classical ZSI, which increases size, cost, and loss; 2) it does not share a dc ground point between the source and converter; 3) the input current is discontinuous, and it requires a decoupling capacitor bank at the front end to eliminate current discontinuity and protect the energy source; and 4) it cannot suppress the inrush current and the resonance introduced by Z-source inductors and capacitors at startup, and the resulting voltage and current spike can destroy the devices.

The start-up inrush current problem of the SL-ZSI occurs because the initial voltage across the Z-source capacitors is zero—a huge inrush current flows to the diode Din, Z-source capacitors and charges the capacitors immediately to Vdc/2, as shown in Fig. 3. Then, the Z-source inductors and capacitors resonate, generating the current and voltage spikes.

V. IMPROVED SWITCHED INDUCTOR QUASI ZSI

Compared to Z-source inverter, the switched inductor quasi-Z-source inverter (SL-QZSI) provides a higher dc-link voltage while remaining the continuous input current and a common ground with the dc source. In some new energy power generation systems, the input voltage is environmental affected and sometimes is too low, thus the boost ability of SL-QZSI may be still not enough. By just replace one of the diodes in switched inductor unit with a capacitor, an improved unit is established.

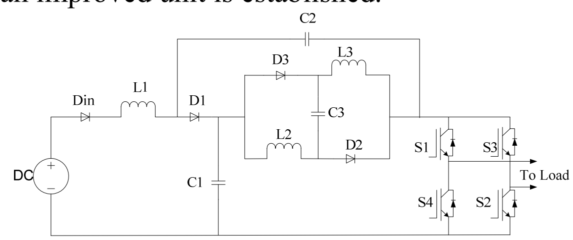

Fig. 4:Improved Switched Inductor Quasi ZSI (ISL-QZSI)

The proposed I-SL-QZSI has an improved boost factor while keeping the advantage of SL-QZSI. For the same input and output voltage, I-SL-QZSI can greatly reduce the shoot-through time, so the conduction loss in shoot through state can be decreased, and the efficiency can be improved.

VI. Control Technique

Pulse width modulated (PWM) inverters are in the middle of the most used power-electronic circuits in simulation and practical applications. These inverters are capable of producing ac voltages of variable magnitude as well as variable frequency.

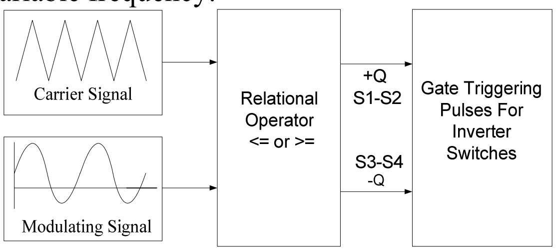

Fig. 5: Block Diagram of SPWM Control Technique

In Sine-PWM inverter the widths of the pole-voltage pulses, over the output cycle, vary in a sinusoidal manner. The scheme, in its simplified form, involves comparison of a high frequency triangular carrier voltage with a sinusoidal modulating signal that represents the desired fundamental component of the pole voltage waveform. The peak magnitude of the modulating signal should remain limited to the peak magnitude of the carrier signal. The comparator output is then used to control the upper side and lower side switches of the inverter.

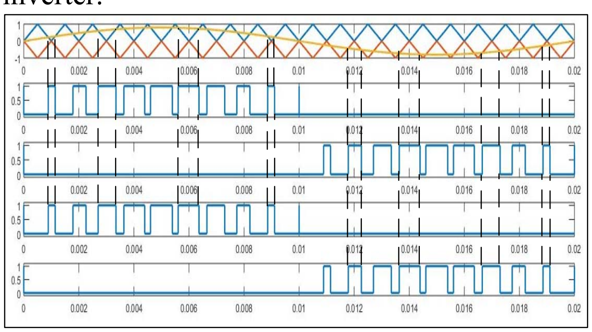

Fig. 6: Sine PWM Control Technique

- What Is Modulation Index?

Modulation Index is the ratio of peak magnitudes of the modulating waveform and the carrier waveform. It relates the inverter's dc-link voltage and the magnitude of pole voltage (fundamental component) output by the inverter. Now let '$V_m \sin(\omega t)$' be the modulating signal and let the magnitude of triangular carrier signal vary between the peak magnitudes of $+V_c$ and $-V_c$. The ratio of the peak magnitudes of modulating wave (V_m)and the carrier wave (V_c) is defined as modulation-index(m). In other words:

$$m = \frac{V_m}{V_c}$$

Normally the magnitude of modulation index is limited below one (i.e., 0<m<1).

VII. Simulation And Results

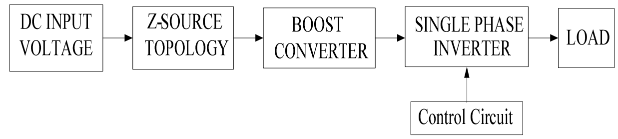

Fig. 7: Block Diagram of ZSI Simulation

TABLE 2: 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
LC Filter	L	160 µH
	C	1000 µF
Load	R	40 Ω
	L	5 mH
Inverter Switching Frequency	5 kHz	

A. *Simulation Results of Z-Source Inverter*

- Z-Source Output Voltage with 0.8 M I:-

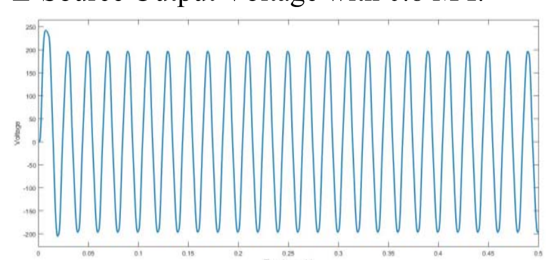

Fig. 8: Output Voltage of Z-Source Converter

- Z-Source Output Voltage THD with 0.8 M I:-

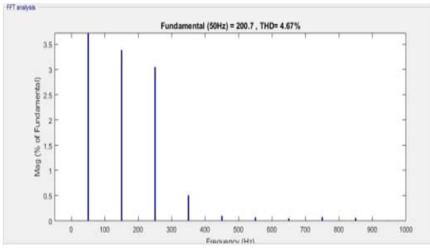

Fig. 9: Output Voltage THD of Z-Source Converter

- Z-Source Output Current with 0.8 M I:-

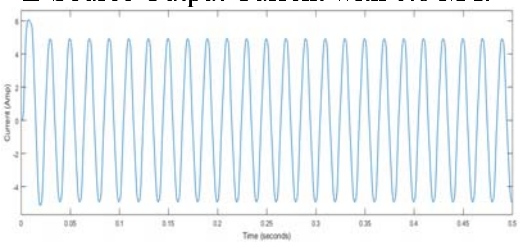

Fig. 10: Output Current of Z-Source Converter

- Z-Source Output Current THD with 0.8 M I:-

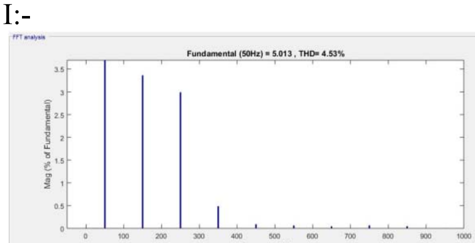

Fig. 11: Output Current THD of Z-Source Converter

B. Simulation Results of Switched Inductor Z-Source Inverter

- SL-ZSI Output Voltage with 0.8 M I:-

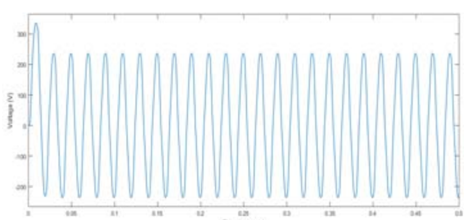

Fig. 12: Output Voltage of SL-ZSI

- SL-ZSI Output Voltage THD with 0.8 M I:-

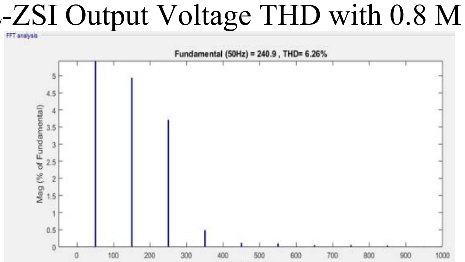

Fig. 13: Output Voltage THD of SL-ZSI

- SL-ZSI Output Current with 0.8 M I:-

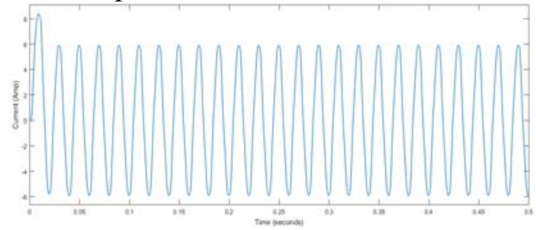

Fig. 14: Output Current of SL-ZSI

- SL-ZSI Output Current THD with 0.8 M I:-

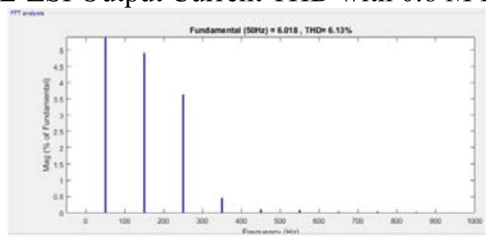

Fig. 15: Output CurrentTHD of SL-ZSI

C. Simulation Results of Switched Inductor Quasi Z-Source Inverter

- SL-QZSI Output Voltage with 0.8 M I:-

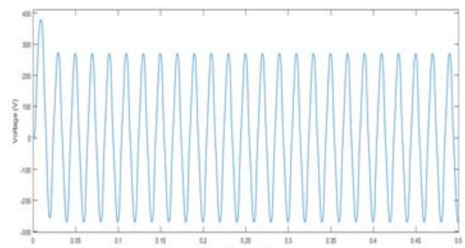

Fig. 16: Output Voltage of SL-QZSI

- SL-QZSI Output Voltage THD with 0.8 M I:-

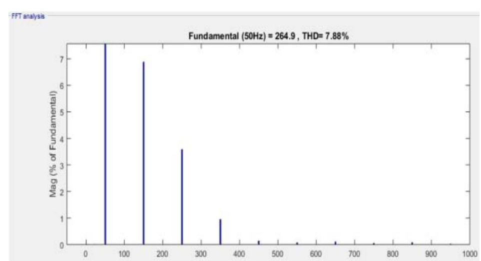

Fig. 17: Output Voltage THD of SL-QZSI

- SL-QZSI Output Current THD with 0.8 M I:-

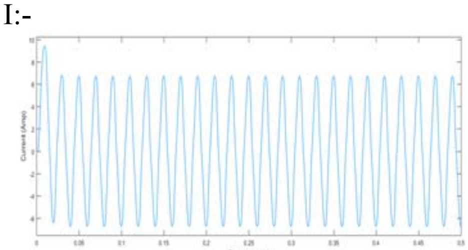

Fig. 18: Output Current of SL-QZSI

- SL-QZSI Output Current THD with 0.8 M I:-

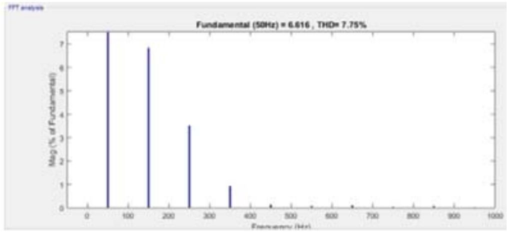

Fig. 19: Output Current THD of SL-QZSI

D. Simulation Results of Improved Switched Inductor Quasi Z-Source Inverter

- ISL-QZSI Output Voltage with 0.8 M I:-

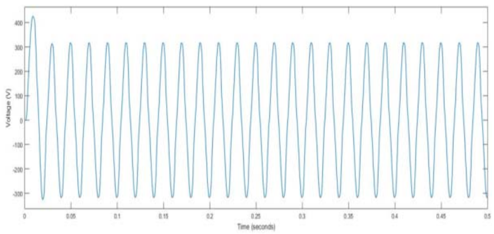

Fig. 20: Output Voltage of ISL-IQZSI

- ISL-QZSI Output Voltage THD with 0.8 M I:-

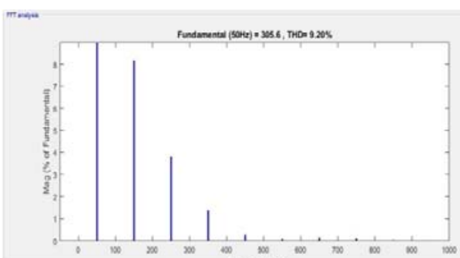

Fig. 21: Output Voltage THD of ISL-QZSI

- SL-IQZSI Output Current THD with 0.8 M I:-

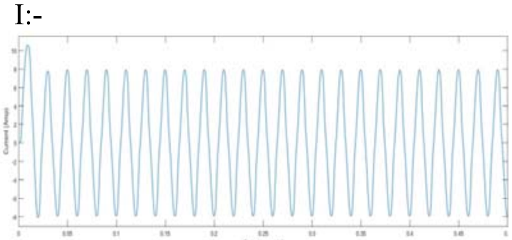

Fig. 22: Output Current of ISL-QZSI

- ISL-QZSI Output Current THD with 0.8 M I:-

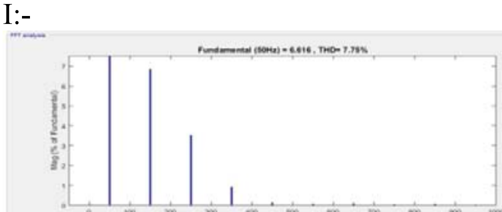

Fig. 23: Output Current THD of SL-QZSI

VIII. COMPARISON OF ZSI, SL-ZSI, SL-QZSI AND ISL-QZSI WITH VARYING MODULATION INDEX

A. Comparison of ZSI, SL-ZSI, SL-QZSI and I-SL-QZSI with 0.8 M.I

TABLE 3: Comparison of ZSI, SL-ZSI, SL-QZSI and I-SL-QZSI with 0.8 M.I

	O/P Vtg.	O/P Vtg. THD	O/P Current	O/P Current THD	Active Power	Reactive Power
ZSI	194.2	4.67	4.869	4.52	502	19.74
SL-ZSI	233.5	6.26	5.85	6.12	724.4	28.45
SL-QZSI	266.9	7.87	6.69	7.74	875.5	34.38
ISL-QZSI	314	9.19	7.87	9.03	1166	45.78

B. Comparison on Output Voltage of ZSI, SL-ZSI, SL-QZSI and I-SL-QZSI with varying M.I

TABLE 4: Comparison Output Voltage of ZSI, SL-ZSI, SL-QZSI and I-SL-QZSI with varying M.I

MI	ZSI O/PVtg.	SL_ZSI O/PVtg.	SL_Q_ZSI O/P Vtg.	I_SL_Q_ZSI O/P Vtg.
0.3	35.44	45.27	53.23	65.68
0.4	60.21	76.29	88.73	105.8
0.5	90.4	113.6	130.3	152.6
0.6	122.4	152.7	174	203.8
0.7	157.7	193.3	220.3	260.3
0.8	194.2	233.5	266.9	314
0.9	233.4	275.3	316.7	364.7

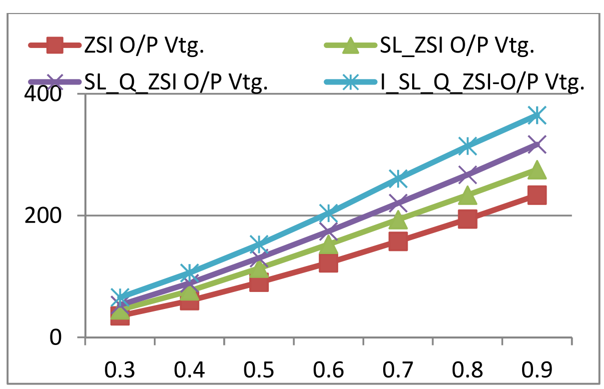

Fig. 24:Output Voltage of ZSI, SL-ZSI, SL-QZSI and I-SL-QZSI with varying M.I

C. Comparison on Output Voltage THD of ZSI, SL-ZSI, SL-QZSI and I-SL-QZSI with varying M.I

TABLE 5: Comparison Output Voltage THD of ZSI, SL-ZSI, SL-QZSI and I-SL-QZSI with varying M.I

M I	ZSI Vtg. THD	SL_ZSI Vtg. THD	SL_Q_ZSI Vtg. THD	I_SL_Q_ZSI Vtg. THD
0.3	5.68	5.52	5.34	5.63
0.4	5.33	5.37	5.22	6.21
0.5	4.81	5.16	5.57	6.8
0.6	4.64	5.42	6.29	7.59
0.7	4.52	5.76	7.13	8.3
0.8	4.67	6.26	7.87	9.19
0.9	4.92	6.83	8.65	9.97

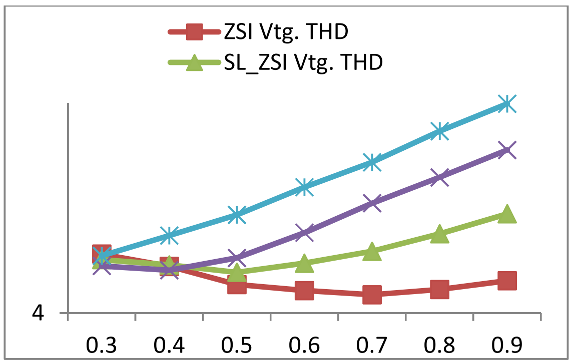

Fig. 25:Output Voltage THD of ZSI, SL-ZSI, SL-QZSI and I-SL-QZSI with varying M.I

D. Comparison on Output Current of ZSI, SL-ZSI, SL-QZSI and I-SL-QZSI with varying M.I

TABLE 6: Comparison Output Current of ZSI, SL-ZSI, SL-QZSI and I-SL-QZSI with varying M.I

M I	ZSI O/P I	SL_ZSI O/P I	SL_Q_ZSI O/P I	I_SL_Q_ZSI-O/P I
0.3	0.88	1.13	1.33	1.64
0.4	1.51	1.91	2.22	2.65
0.5	2.25	2.84	3.26	3.82
0.6	3.06	3.82	4.36	5.11
0.7	3.95	4.84	5.52	6.52
0.8	4.869	5.85	6.69	7.87
0.9	5.853	6.9	7.94	9.14

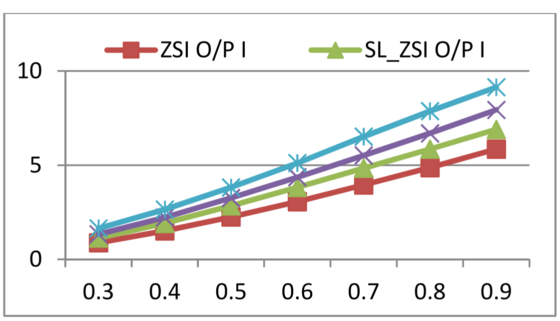

Fig. 26:Output Current of ZSI, SL-ZSI, SL-QZSI and I-SL-QZSI with varying M.I

E. Comparison on Output Current THD of ZSI, SL-ZSI, SL-QZSI and I-SL-QZSI with varying M.I

TABLE 7: Comparison Output Current THD of ZSI, SL-ZSI, SL-QZSI and I-SL-QZSI with varying M.I

M I	ZSI I THD	SL_ZSI I THD	SL_Q_ZSI I THD	I_SL_Q_ZSI-I THD
0.3	5.47	5.3	5.11	5.32
0.4	5.13	5.17	5.02	5.94
0.5	4.62	4.97	5.38	6.57
0.6	4.47	5.26	6.13	7.39
0.7	4.36	5.61	6.99	8.12
0.8	4.52	6.12	7.74	9.03
0.9	4.79	6.7	8.53	9.81

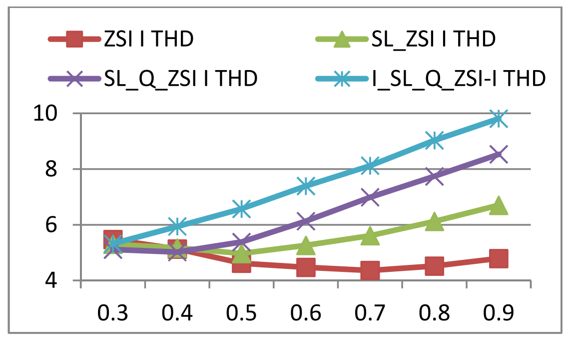

Fig. 27: Output Current THD of ZSI, SL-ZSI, SL-QZSI and I-SL-QZSI with varying M.I

F. Comparison on Output Active Power of ZSI, SL-ZSI, SL-QZSI and I-SL-QZSI with varying M.I

TABLE 8: Comparison Output Active Power of ZSI, SL-ZSI, SL-QZSI and I-SL-QZSI with varying M.I

M I	ZSI Activ e	SL_Z SI Active	SL_Q_Z SI Active	I_SL_Q_Z SI Active
0.3	18.16	29.49	40.27	60.73
0.4	51.67	82.51	108.7	151.6
0.5	113.1	179.8	226.3	299.9
0.6	205.3	319.7	391.8	516.2
0.7	334.1	502	608	820
0.8	502	724.4	875.5	1166
0.9	724.4	998.9	1212	1545

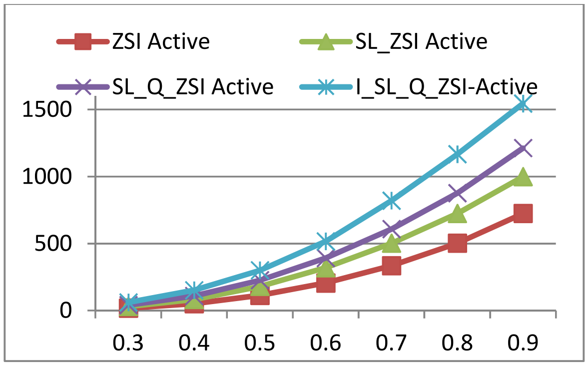

Fig. 28: Output Active Power of ZSI, SL-ZSI, SL-QZSI and I-SL-QZSI with varying M.I

G. Comparison on Output Reactive Power of ZSI, SL-ZSI, SL-QZSI and I-SL-QZSI with varying M.I

TABLE 9: Comparison Output Reactive Power of ZSI, SL-ZSI, SL-QZSI and I-SL-QZSI with varying M.I

MI	ZSI Reactive	SL_ZSI Reactive	SL_Q_ZSI Reactive	I_SL_Q_ZSI Reactive
0.3	0.713	1.158	1.581	2.38
0.4	2.02	3.24	4.26	5.95
0.5	4.44	7.06	8.88	11.77
0.6	8.063	12.55	15.39	20.27
0.7	13.12	19.72	23.88	32.21
0.8	19.74	28.45	34.38	45.78
0.9	28.45	39.23	47.59	60.68

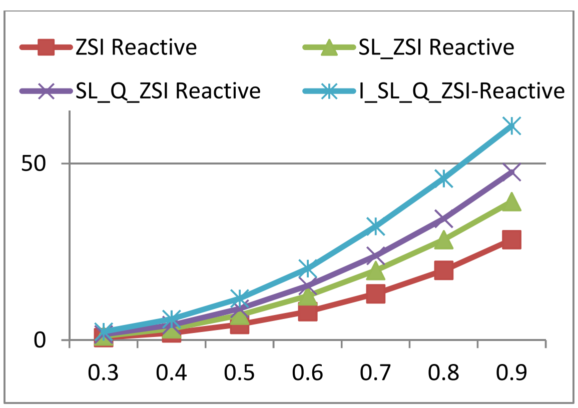

Fig. 29:Output Reactive Power of ZSI, SL-ZSI, SL-QZSI and I-SL-QZSI with varying M.I

VIII. CONCLUSION

This paper has presented an impedance-source power converter called as ZSI for implementing dc-to-ac power conversion and compares that with the advance topologies of ZSI. The Z-source inverter employs a unique impedance network which coupled between the inverter main circuit and the power source.

From the above comparisons the ZSI output magnitude gets increase with the modification done in the topologies and it also gets increase or decrease with the change in modulation index. The buck-boost operation is shown in above comparison, so as to satisfy the operating level as per the system.

REFERENCES

[1] Fang Zheng Peng "Z-Source Inverter", IEEE Trans. On Industry Applications, vol. 39, no. 2, pp. 504-510, March/April 2003.

[2] Yuan Li, Joel Anderson, Fang Z. Peng, and Dichen Liu, "Quasi-Z-Source Inverter for Photovoltaic Power Generation Systems" Twenty-Fourth Annual IEEE Applied Power Electronics Conference and Exposition, pp. 918-924, Feb. 2009.

[3] Miao Zhu, Member, Kun Yu and Fang Lin Luo, "Switched Inductor Z-Source Inverter", IEEE Transactions On Power Electronics, vol. 25, no. 8, pp. 2150-2158, August 2010.

[4] Minh-Khai Nguyen, Young-Cheol Lim and Geum-Bae Cho, "Switched-Inductor Quasi-Z-Source Inverter", IEEE Trans. On Power Electronics, vol. 26, no. 11, pp. 3183-3191, Nov. 2011.

[5] Hailong Liu, Yuyao He, Mingyang Zhang Liu, "Quasi-Switched-Inductor Z-Source Inverter", 2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia), pp. 1222-1229, May 2016.

[6] Xiaoxia Liang, Jinbin Zhao, Keqing Qu, Jianfeng Dai, "Novel Z-Source High Step-up Boost Converter", 2014 International Power Electronics and Application Conference and Exposition, pp. 11-15, Nov. 2014.

[7] Kai Deng, Jianyong Zheng, Jun Mei, "Novel Switched-Inductor Quasi-Z-source Inverter", Journal of Power Electronics, Vol. 14, No. 1, pp. 11-21, January 2014

[8] Saeid Khani, Leila Mohammadian, Seyed Hosseini, Karim Roshan Milani, "Application of Embedded Z-Source Inverter in Grid Connected Photovoltaic System", 18th Electric Power Distribution Conference, pp. 1-5, May 2013.

[9] Dr. P. H. Zope, Dr. A. J. Patil, Dr. Ajay Somkuwar, "Performance and Simulation

Analysis of Single Phase Grid Connected PV System Based On Z-Source Inverter" , 2010 Joint International Conference on Power Electronics, Drives and Energy Systems & Power India, pp. 1-6, Dec. 2010.

[10] Miaosenshen, Fang Peng, "Operation Modes and Characteristics of the Z-Source Inverter with Small Inductance or Low Power Factor", IEEE Transactions on Industrial Electronics, Vol. 55, No. 1, pp. 89-96, Jan 2008.

[11] Gokhansen, Malik E. Elbuluk, "Voltage and Current-Programmed Modes in Control of the Z-Source Converter", IEEE Transactions on Industry Application, Vol. 46, No. 2, pp. 680-686, Mar/Apr 2010.

[12] N. Kalaiarasi, S. Paramasivan, Sanchari Kuntu, "Comparison of Z-Source Inverter with DC-DC Boost Converter fed VSI for PV applications" , 2014 IEEE 2nd International Conference on Electrical Energy Systems (ICEES), pp. 87-91, Jan. 2014.

[13] Fang Zheng Peng, Miaosen Shen, Zhaoming Qian, "Maximum Boost Control of the Z-Source Inverter", IEEE Transaction on Power Electronics, Vol. 20, No. 4, pp. 833-838, July 2005.

[14] Miaosen Shen, Alan Joseph, Jin Wang, Fang Z Peng, Donald J Adams, "Comparison of Traditional Inverter and Z-Source Inverter for Fuel Cell Vehicles", IEEE Transactions on Power Electronics, Vol. 22, pp. 1453-1463, July 2007.