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Design and Implementation of Z-source inverter using SBC

Mrudul A. Mawlikar
M.E. Power Electronics and Drives
Department of Electrical Engineering
Fr.C.Rodrigues Institute of Technology,
Navi Mumbai, Maharashtra, India.
mmawlikar@yahoo.com

Ms. Sreedevi S Nair
Assistant Professor
Department of Electrical Engineering
Fr.C.Rodrigues Institute of Technology,
Navi Mumbai, Maharashtra, India.
sreedevifcrit@gmail.com

***Abstract*— This paper presents a comprehensive design and hardware implementation of Z-source inverter. For most of the renewable applications, the conventional VSI has been used which requires an additional boost converter to boost the output voltage. Z-source inverter provides a single stage power conversion topology which can give both voltage buck and boost properties. The control method used in the Z-source inverter is the Simple Boost Control (SBC) technique with Sinusoidal pulse width modulation. The design of the impedance network, hardware results of single stage Z-source inverter are presented in this paper.**

Keywords—Z-source inverter, SBC.

I. INTRODUCTION

Traditional inverters are categorised into two types namely Voltage Source Inverters (VSI) and the Current Source Inverters (CSI). VSI is a single phase or a three phase bridge inverter fed from a DC voltage source such as a battery or an AC voltage source with a diode rectifier circuit. The AC output voltage of a VSI doesn't exceed the DC input voltage. In many applications where renewable energy sources such as PV, Fuel cell is used, the input DC voltage is not always constant. In such cases a DC/DC boost converter is utilized to boost the DC input voltage to meet the required AC output voltage. This increases the system cost and complexity.[1][2]

The VSI has a disadvantage that the two switches of the same leg cannot be gated on at the same time. This is expressed as Shoot through state, which will destroy the inverter. A dead time is introduced to avoid switching ON of two switches in the same leg simultaneously. This results into harmonic issues and output voltage distortion.

Likewise, in a CSI, the DC current at the input is maintained constant with a small ripple by using a large inductor fed from a voltage source. The output voltage of a CSI is greater than the DC input voltage. In a single phase CSI, at least one of the upper switches and one of the lower switches should be maintained on at any time. Else, an open circuit problem occurs which destroys the inverter. Also to have reverse blocking capability, a series diode is used in combination with the switches of the inverter.

The traditional inverters have a limitation that they can have either buck or boost operation only. Open or short circuit conditions result in the damage of the devices. To overcome the problems associated with the traditional VSI and CSI, an impedance source inverter or Z-source inverter is presented in this paper. This methodology was first proposed by F.Z.Peng in the year 2002[1]. Z-source inverter operates as a buck-boost inverter without using the DC-DC converter bridge due to its unique circuit topology.

Z-source inverter utilises a LC impedance network for coupling the inverter circuit to the power source. It also allows the use of shoot through switching states, which eliminates the need for dead times that are used in traditional inverters. The Z-source inverter consists of two inductors L_1 and L_2 and two capacitors C_1 and C_2 connected in an X shape.[3]

This paper presents a comprehensive design and hardware implementation of a single phase Z-source inverter. In most PV applications, since the PV output voltage is low, a two stage conversion topology is used as shown in Fig.1. First the PV voltage is boosted to the required DC output voltage by a boost converter, which is then converted to an AC voltage by using a single phase VSI. The input voltage V_{dc} could be provided by solar panel.

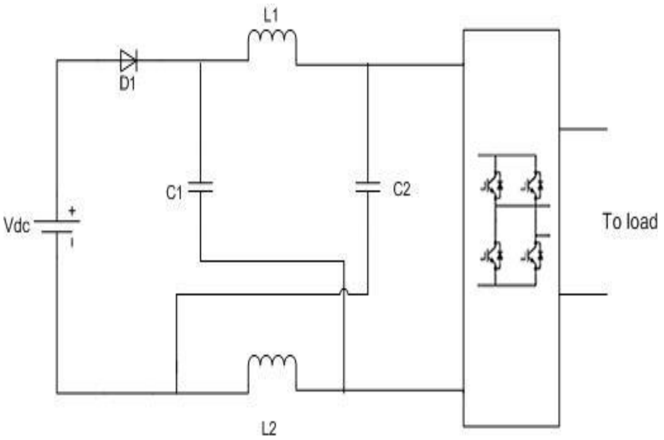

Fig: 1. Z-source Inverter used for PV applications

Fig: 1 represents the Z-source inverter implemented for such applications. Z-source inverter can straightaway produce an AC output voltage greater or less than the input PV voltage. The input diode D_1 is reverse blocking diode used to prevent the reverse current flow to the source.

II. Z SOURCE INVERTER

A. *Working Principle*

The Z source inverter is established on the Z source network which can be used to buck or boost the input DC voltage. It utilizes the forbidden state (inverter shorted state) for the buck and boost of the input voltage. The concept of boosting the input voltage is based on the ratio of 'shoot through' time to the whole switching period. The impedance network consists of capacitors C1, C2 and inductors L1, L2 connected in X shape to provide an impedance source coupling the inverter to DC source. The inductors are responsible for eliminating the inrush current and harmonics of the current waveform. It forms a second order filter and handles undesirable voltage sags of the DC source. The Z source concept can be applied to all AC-AC, DC-DC, DC-AC and AC-DC conversion. The circuit diagram of a single phase Z-source inverter is shown in Fig:2.[1][4]

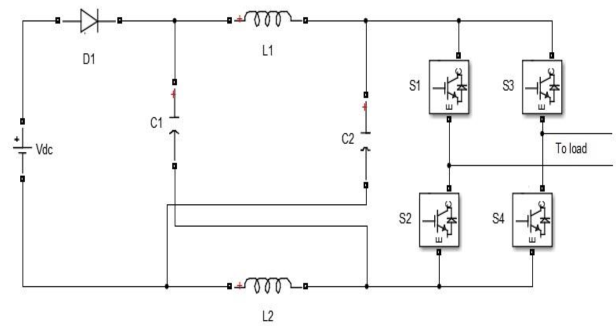

Fig. 2. Z source inverter

In single phase Z source inverter, an additional control parameter is introduced namely the Boost factor (B), which modifies the AC output voltage of traditional 1-phase PWM inverter as shown in "(1)".[1][4]

$$V_{out} = BMV_{DC} \quad (1)$$

V_{out} is maximum sinusoidal voltage
B is boost factor
M is modulation index
V_{DC} is input voltage
The gain of the inverter is given by G where G=BM.

For a single phase traditional inverter, the AC output voltage is given by "(2)".[1][4]

$$V_{out} = MV_{DC} \quad (2)$$

The inverter gain can be expressed as $G = BM$

The modulation index also called as amplitude modulation ratio (M) is defined as ratio of amplitude of reference wave to the amplitude of carrier wave as shown in "(3)".[1][4]

$$M = \frac{V_{ref}}{V_{car}} \quad (3)$$

The shoot through duty ratio is given by "(4)"

$$D_0 = \frac{T_0}{T} \quad (4)$$

where T_0 is shoot through interval and
T is switching period

The boost factor is resulting from the shoot through state which is introduced for a short period of time in one complete switching cycle and is expressed by "(5)".[1][4]

$$B = \frac{1}{1-2D_0} \quad (5)$$

B. *Modes of operation of Z source inverter*

The operation of Z source inverter can be separated into three states namely: Active, Zero and Shoot through state as shown in Table 1.[4]

TABLE 1. Switching states of Z-source inverter

Switching states	**S1**	**S2**	**S3**	**S4**
Active state	1	0	0	1
	0	1	1	0
Zero state	1	0	1	0
	0	1	0	1
Shoot through state	1	1	S3	S4
	S1	S2	1	1
	1	1	1	1

Z source inverters are implemented with the view of boosting the voltage by utilizing the forbidden shoot through state in the traditional inverters. The impedance network is assumed to be symmetrical which gives us

$C1=C2=C$ and $L1=L2=L$

Voltage across inductors and capacitors is given as

$V_{L1}=V_{C1}$, $V_{L2}=V_{C2}$

1. Active state

This state represents the operation of inverter in one of traditional active states where inverter bridge acts as a current source viewed from the DC link.[4]

2. Zero state

This state represents the operation of inverter in one of the traditional zero state where the inverter is open circuited as viewed from Z source circuit. This occurs due to switching of either both the upper devices or both the lower devices in inverter leg.[4]

3. Shoot through state

This state represents the operation in the forbidden state. This mode is incorporated in every switching cycle during traditional zero vector period generated by PWM control. Depending on the voltage boost needed, the shoot through interval (T_0) or its duty cycle (T_0/T) is determined.[4]

III. SIMPLE BOOST CONTROL

There are different modulation techniques for controlling the z-source inverter. The modulation techniques are classified based on the different shoot through states insertion methods. One of the simplest modulation scheme employed is the Simple Boost Control (SBC) technique where z-source inverter is used in the boost mode. This control strategy maintains the seven states shown in table and are unchanged as in traditional carrier based PWM. Two straight lines are employed to comprehend shoot through duty ratio (D_0). The first straight line is equal to the positive peak value of sinusoidal reference voltage while the second is equal to the negative peak value. When the triangular carrier signal is greater than positive straight line or smaller than the negative straight line, the inverter operates in shoot through or else it operates as traditional PWM inverter. The block diagram used for implementing simple boost control technique is shown in Fig.3.[5]

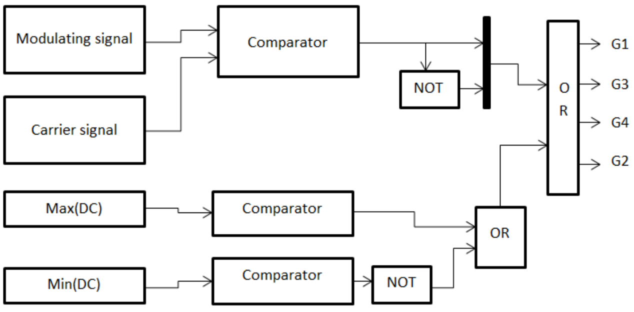

Fig. 3. Block diagram of Simple boost modulation scheme

Since positive straight line equals maximum sinusoidal voltage and negative straight line equals minimum sinusoidal voltage, the modulation index (M) and shoot through duty ratio (D_0) are interdependent on each other. The relation between these parameters is expressed in "(6)". We can observe from "(6)" that the shoot through duty ratio decreases with increase in modulation index.[5]

$$D_0 = 1\text{-}M \tag{6}$$

The boost factor is given by "(7)" as shown below[5]

$$B = \frac{1}{2M-1} \tag{7}$$

Also from "8" inverter gain can be expressed as[5]

$$G = BM = \frac{M}{2M-1} \tag{8}$$

IV. DESIGN OF Z SOURCE INVERTER

The design of the Z-source converter consists of the designing of capacitors C1, C2 and inductors L1, L2. Owing to the symmetry of the network, L1=L2=L and C1=C2=C. Calculation of the average current of an inductor is carried out by using the relation "(9)" as shown below:[3]

$$I_L = P/V_{DC} \tag{9}$$

where P is the total power and V_{DC} is input voltage.

Considering the total power to be 200 W and DC input voltage as 30 V, we get the average inductor current value to be 1.69 A. Also considering the modulation index (M) as 0.67, we get the shoot through duty ratio as 0.33.

The capacitor voltage V_C is given by "(10)"[3]

$$V_C = \frac{(1-D_0)}{(1-2D_0)} * V_{DC} \tag{10}$$

Calculation of inductance L for impedance network is carried out by "(11)"[3]

$$L = \frac{T_0 * V_C}{I_L} \tag{11}$$

where T_0 is shoot through period per switching cycle.

Substituting the shoot through period of 33µsec and capacitor voltage and inductor current from "(9)" and "(10)" respectively, we get inductor value as L = 4.233mH.

The purpose of capacitor is to absorb the current ripple and maintain a fairly constant voltage so as to keep output voltage sinusoidal. To limit capacitor voltage ripple to 3%, the required capacitance is calculated by "(12)"[3]

$$C = \frac{T_0 * I_L}{V_C * 3\%} \tag{12}$$

Substituting the value from "(12)", we get the capacitor value as 10µF.

V. HARDWARE RESULTS

The simulation of single phase Z source inverter was performed in MATLAB-SIMULINK environment. Table 2 shows the specifications of the single phase Z-source inverter. The Matlab model of the same circuit is shown in Fig:4. Fig:5 shows the filtered ac output of 91 V_{peak} obtained by simulation. Detailed explanation of the simulation models of single phase Z-source inverter and Simple Boost modulation scheme is presented in previous paper.[6][7][8]

TABLE 2. Specifications of Z-source inverter

Sr.no	Parameters	Values

1	Input DC voltage	30V
2	Switching frequency	10kHz
3	Modulation index	0.67
4	Filter	Lf= 3mH Cf= 23µF
5	Load	R= 300Ω L= 2mF

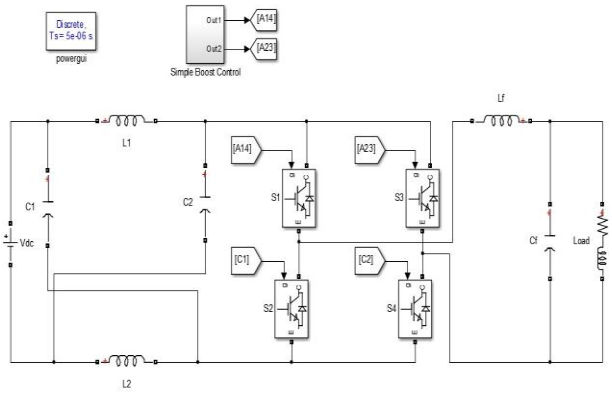

Fig. 4. Matlab Model of the single phase Z-source inverter

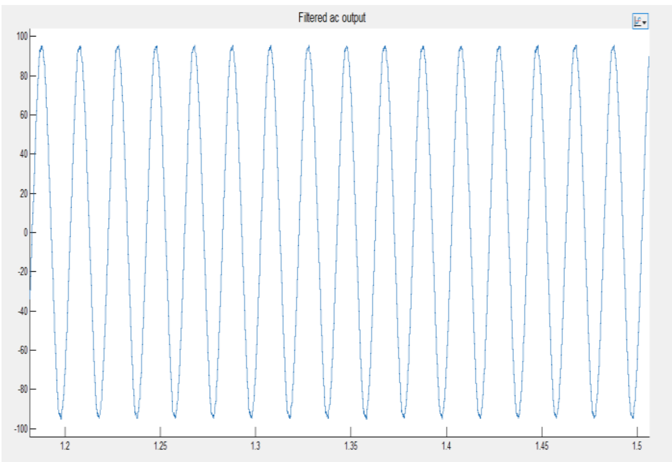

Fig. 5. Filtered ac output

The hardware prototype consists of power circuit (Z-source inverter), driver circuit and auxiliary power circuit. The block diagram of hardware setup is show in Fig.6. The hardware consists of dc supply, power circuit, driver circuit, voltage regulator, Digital Signal Processor(DSP) and load. The power circuit consists of Z-source inverter which is fed by dc supply which gives desirable ac output. The single phase inverter is constructed using four IGBT switches. These IGBT switches are controlled using the gating signals generated in the DSP TMS320F28069 in accordance with the simple boost control scheme.

The gating pulses from the DSP are given to the buffer circuit to prevent loading of DSP. Further it is connected to HCPL3120 driver circuit which provides isolation and power amplification to the gating pulses. DSP interfacing circuit consists of 1.5 volts dc offset providing circuit, voltage divider circuit and anti-parallel Zener diodes to restrict the value of signals fed to DSP from 0 to 3.3V. The gate driver circuit is powered by an auxiliary power supply. The hardware components specifications are shown in table 3.The boost factor of Z-source inverter according to "(7)" is calculated to 2.94.

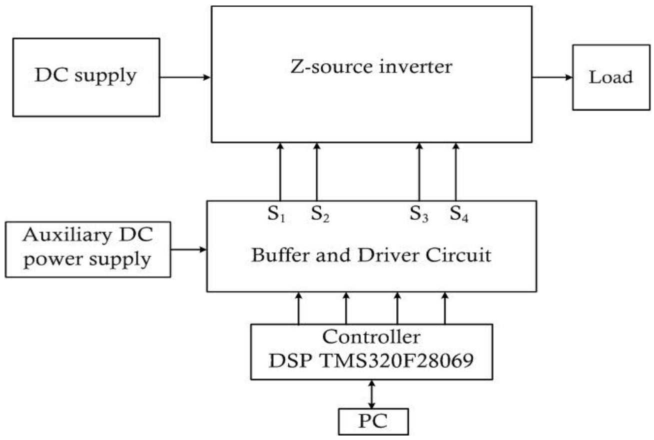

Fig. 6. Block diagram of hardware implementation

TABLE 3. Hardware components

Sr.no	Parameters	Values
1	IGBT Switch	600V/60A

	FGH60N60UFD	
2	Diode DSEI-60-06	600v, 60A Diode
3	Inductors(L1,L2)	4.233mH
4	Capacitors(C1,C2)	100µF
5	Buffer IC	74HCT573
6	Gate Driver	HCPL3120
7	DSP	TMS320F28069
8	Filter	Lf= 3mH Cf= 23µF
9	Load	R= 300Ω L= 2mF

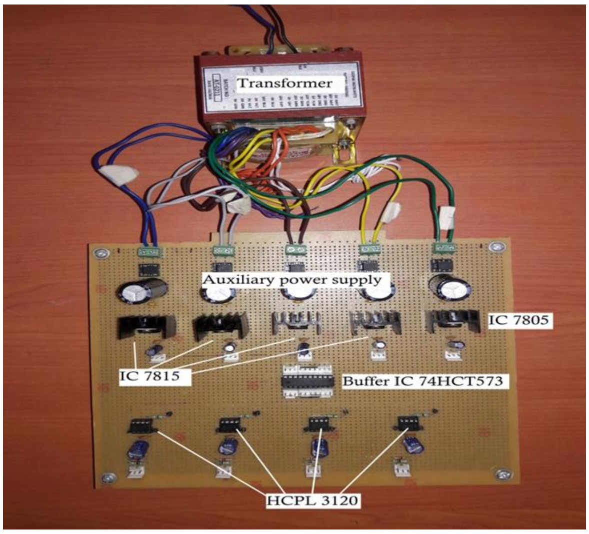

Fig.7. Hardware prototype of auxiliary supply and buffer circuit

Fig.7 shows the hardware implementation for auxiliary power supply and driver circuit board. The stepped down ac supply fed through the step down transformer of rating 230V/18V. The ac voltage is then converted into dc by use of diode bridge rectifier. Further arrangements can then be seen into the schematic diagram. Driver circuit is connected to the auxiliary power supply thus providing gate pulses to IGBT switches.

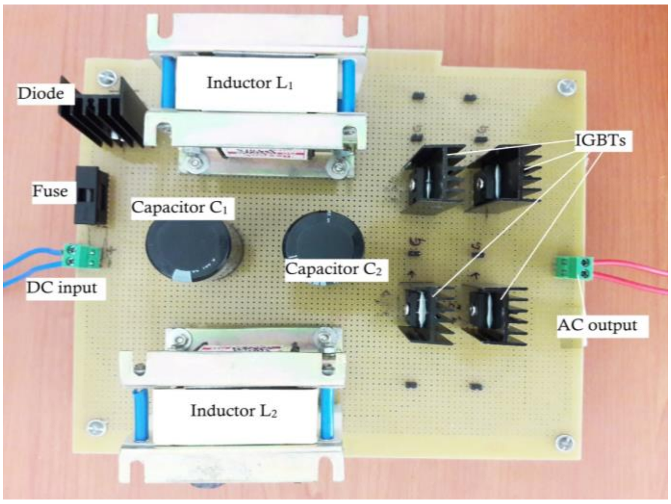

Fig.8. Hardware prototype of Z-source inverter

The hardware implementation of Z-source inverter is shown in Fig.8. The hardware setup is shown in Fig.9. Four IGBTs with their heat sink are mounted in the circuit. A fuse of 4A is incorporated in series to the input of the circuit which provides over current protection to the circuit. The switch voltage rating is taken two to three times that of the dc link voltage of 213V according to "(10)". The current rating is taken more than ten times that of the output current of 1.69A. By taking into consideration the above mentioned constraints, availability and cost, IGBT FGH60N60UFD is selected for hardware implementation.

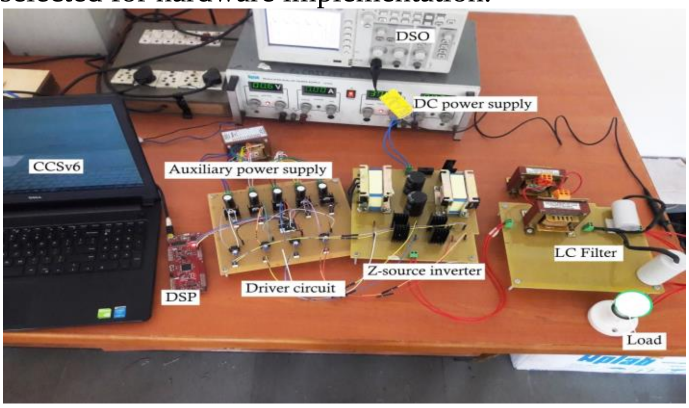

Fig. 9. Hardware setup

The gating pulses that are given to switches S_1 and S_2 are shown in Fig.10(a) and that to switches S_3 and S_4 are shown in Fig.10(b). The pulses have been generated using DSP TMS320F28069 in accordance with the Simple Boost Control (SBC) technique and incorporate a shoot through overlap time of 33µ seconds. On observation, it is clear that the DSP gives pulse with a voltage which is insufficient to drive the switch. These pulses are then given to the buffer circuit which boosts it upto 15V and are provided to inverter switches. The gating pulses from the DSP are used to switch the inverter and provide desirable ac output. The results obtained by open loop control are tabulated in table 4.

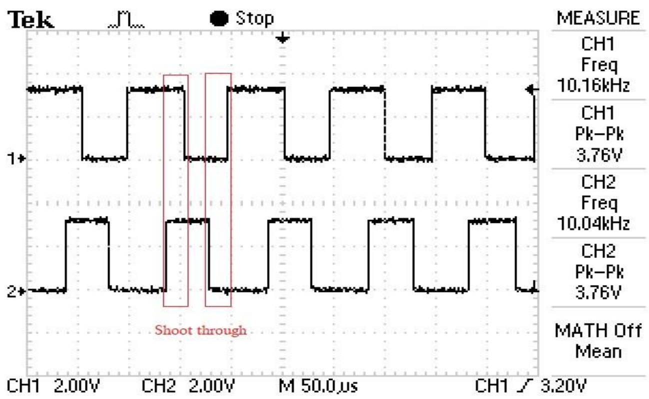

Fig 10.a. Pulses to switch S1 and S2

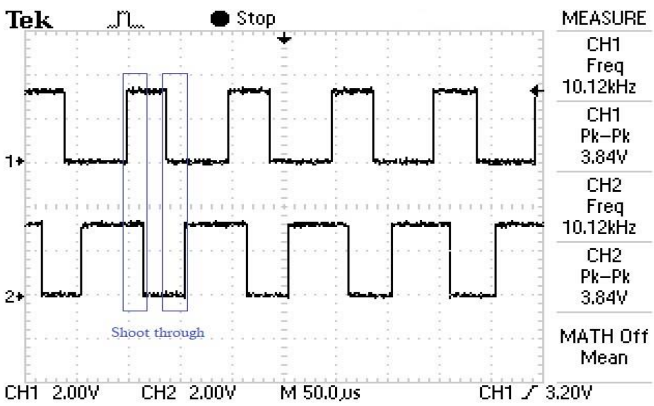

Fig 10.b. Pulses to switch S4 and S3

TABLE 4. Hardware results

Sr.no.	Input Voltage(V_{DC})	Output Voltage(V_{peak})
1	10	22.4
2	15	36.8
3	20	56
4	25	70
5	30	86

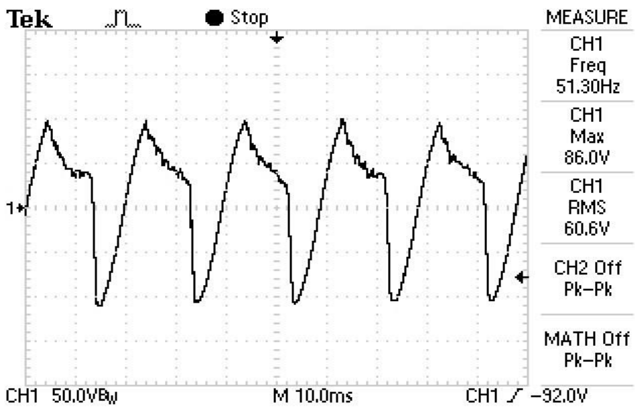

Fig 11. Output voltage of Z-source inverter

Fig.11 represents the filtered ac output voltage of 86V peak for an input of 30V and displayed on DSO(Digital Signal Oscilloscope). On observation, it can be seen that the output voltage is boosted by a factor of 2.8. It is clear that the output sine waveform has certain anomaly to its shape. This anomaly in the output waveform is due to the noise and voltage associated with it which is introduced from the transformer through driver circuit. Also this anomaly can be credited to the imbalance in the impedance network which is introduced because of unequal inductor values. Nonetheless the output waveform is boosted to desired value and is sufficient to drive the load connected in the hardware prototype.

VI. CONCLUSION

This paper has presented a comprehensive design and hardware implementation of Z-source inverter. The Simple Boost Control Method is used to insert the shoot through zero state which provides the unique buck-boost feature to this inverter. By adjusting the boost factor, the Z-source inverter can yield an ac output voltage which is greater than the input voltage, which is impossible in the conventional inverters. The Z-source inverter overcomes the shortcomings of a traditional VSI and produces a novel power conversion concept.

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