

Identification of an Effective Control Scheme for Z-source Inverter

T. Meenakshi¹ K. Rajambal²

Abstract – This paper presents a comparative analysis of the Z-source inverter with two different control techniques namely the simple boost control and the maximum constant boost control with third harmonic injection. The Z-source inverter has the capability to buck-boost the input voltage without any intermediate boost conversion stage. It utilizes the shoot-through states effectively to boost the input voltage. A model of the Z-source inverter is built in MATLAB/SIMULINK and its performance is analyzed with the two control schemes. The effective scheme is identified based on the current and voltage waveforms, voltage gain and voltage stress. The experimental result on a prototype inverter validates the simulation results.

Keywords – Boost factor, modulation index (M), shoot-through, voltage gain, Z-source inverter.

I. INTRODUCTION

In conventional voltage source inverters, the output voltage is always less than the input DC voltage. Also, firing the thyristors in the same leg is restricted as it short circuits the DC source [1-3]. To overcome the above said limitations, the Z-source inverter is proposed in [4]. The Z-source inverter uses a Z impedance network comprising of L and C components as the front end of the conventional inverter. The buck and boost modes of operation is achieved by adjusting the shoot through periods. Further, the shoot-through state caused by the electromagnetic interference will not destroy the circuit [5]. Therefore a more reliable single stage power converter for both buck and boost operation is obtained.

The firing scheme of the traditional PWM inverter discussed in [6]-[8] is to be modified to include the shoot through states. A simple control technique is introduced in [4] in which dc references are used to generate the shoot through state. Ref. [9] discusses the continuous and discontinuous modes of operation of Z-source inverter using modified PWM technique. The maximum boost control technique for the Z-source inverter is explained in [10]. To reduce the current ripple and voltage stress on the inverter maximum constant boost with third harmonic injection is proposed in [11]. The digital implementation of the firing scheme is discussed in [12].

In this paper, the modeling, simulation and analysis of a Z-source inverter with two different control techniques is carried out. The firing pulses are generated using simple boost control and maximum constant boost with third harmonic injection techniques in Matlab/Simulink environment.

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¹ Department of Electronics and Communication Engineering, IFET college of Engineering, India, E-mail: mechand22@gmail.com

² Department of Electrical and Electronics Engineering, Pondicherry Engineering College, India, E-mail: rajambalk@gmail.com

The inverter is simulated with different input voltages and the effect of modulation index is studied for the firing schemes. Based on the voltage gain and voltage stress the better scheme is identified. The simulation results are validated with the prototype model.

II. Z-SOURCE INVERTER

Fig. 1 shows the circuit of the Z-source inverter. It is a buck boost inverter and has a wide range of obtainable voltage. A Z-impedance network is present at the front end of the inverter which consist of two inductors (L_1, L_2) and two capacitors (C_1, C_2) connected in X fashion. This Z-impedance network helps to boost the input voltage.

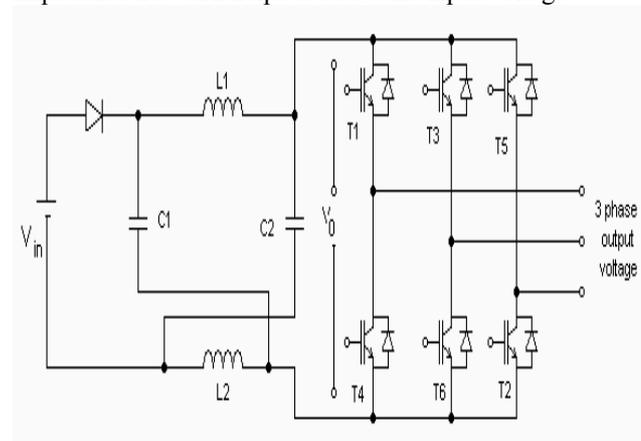


Fig. 1: Z-source inverter

The voltage boost is obtained by the introduction of shoot through states in the firing pulses. During the shoot through state, both the thyristors of the same phase leg conduct and the inverter becomes a short circuit. Fig. 2a shows the switching chart of the Z-source inverter. The shoot through period indicates the conduction of both switches in the same leg. The time period of the shoot through state is given as T_0 . The time period of the non shoot through state is given as T_1 . The sum of the shoot through period and non shoot period gives the total time period of the pulse (T).

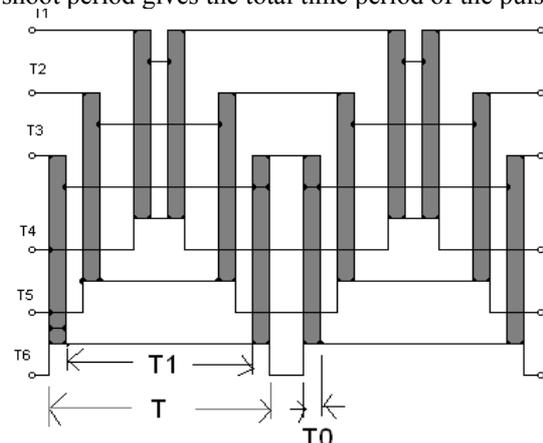


Fig. 2a: Switching chart of Z-source Inverter

The equation of the output voltage of the Z-source inverter and the boost factor is determined with the Fig. 2b. It shows the Z-source network during the shoot-through state. The inductor is energized during this state and the inductor voltage increases due to the increasing current. The capacitor is connected in parallel to the inductor and its voltage is boosted. During the non-shoot through state this boosted voltage appears across the inverter.

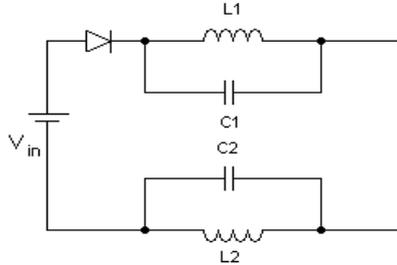


Fig. 2b: Equivalent circuit of Z-source network during the shoot through state

During the shoot through state,

$$V_L = V_c$$

and during the non shoot through state

$$V_L = V_{in} - V_c$$

where V_L is the inductor voltage, V_c is the capacitor voltage of the Z-network and V_{in} is the input DC voltage. [1]

The average voltage of inductor over one switching period is zero which is given by (1).

$$\left. \begin{aligned} V_L &= \frac{T_0 V_c + T_1 (V_{in} - V_c)}{T} = 0 \\ V_c (T_0 - T_1) + T_1 V_{in} &= 0 \\ V_c (T_1 - T_0) &= T_1 V_{in} \end{aligned} \right\} \quad (1)$$

Based on this V_c/V_{in} is obtained as (2)

$$\frac{V_c}{V_{in}} = \frac{T_1}{T_1 - T_0} \quad (2)$$

where T_1 is the time period of non shoot through state and T_0 is the time period of shoot through state.

The capacitor voltage of the Z-network is expressed by (3)

$$\begin{aligned} V_c &= \frac{T - T_0}{T - T_0 - T_0} V_{in} \\ V_c &= \frac{1 - \frac{T_0}{T}}{1 - \frac{2T_0}{T}} V_{in} \end{aligned} \quad (3)$$

where T denotes the total time period.

The peak DC link voltage V_0 appearing across the inverter bridge shown in Fig .1 is derived as follows and is expressed as (4).

$$\begin{aligned} V_0 &= V_c - V_L = 2V_c - V_{in} \\ &= 2\left(\frac{T_1}{T_1 - T_0}\right)V_{in} - V_{in} \\ &= \frac{T}{T_1 - T_0} V_{in} \\ V_0 &= B.V_{in} \end{aligned} \quad (4)$$

where B is the boost factor of the inverter which is given by (5)

$$\begin{aligned} B &= \frac{T}{T_1 - T_0} = \frac{1}{\frac{T_1 - T_0}{T}} = \frac{1}{\frac{T - T_0 - T_0}{T}} \\ &= \frac{1}{1 - 2\frac{T_0}{T}} \end{aligned} \quad (5)$$

T - total time period.

The output peak phase voltage obtained from the Z-source inverter is expressed as (6)

$$\begin{aligned} V_{ac} &= M.V_0 / 2 \\ V_{ac} &= M.B.\frac{V_{in}}{2} \end{aligned} \quad (6)$$

where M is the modulation index of the inverter.

3.1 Simple boost control technique

The firing pulses generated using a simple boost control scheme is shown in Fig. 3. Three sinusoidal reference signals V_a , V_b and V_c and two constant DC voltages are compared with the triangular carrier wave to generate the firing pulse with the shoot through state. The reference signals are phase displaced by 120 degrees and the amplitude of the two straight lines is equal to the peak amplitude of the reference wave.

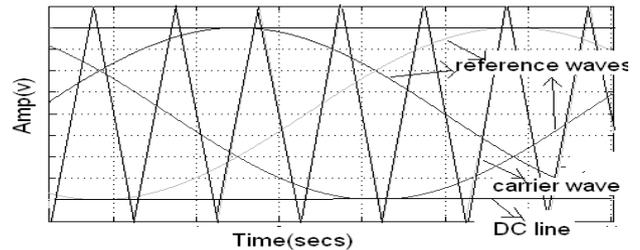


Fig. 3: Simple Boost Control scheme

When the carrier waves is greater than the upper envelope, V_p , or lower than the bottom envelope, V_n , the circuit turns into shoot-through state. Otherwise it operates as traditional carrier based PWM.

The boost factor obtained by the simple boost control technique is given by (6)

$$M = T_1/T$$

$$\begin{aligned} B &= \frac{1}{1 - 2T_0/T} = \frac{1}{1 - 2(T - T_1)/T} \\ &= \frac{1}{1 - 2 + 2M} = \frac{1}{2M - 1} \end{aligned} \quad (7)$$

Equation (7) gives the voltage gain obtained with the simple boost control technique.

$$G = \frac{V_{ac}}{V_{in}/2} = MB = \frac{M}{2M - 1} \quad (8)$$

The peak phase voltage of the Z-source inverter is given by (8)

$$V_{ac} = MB\frac{V_{in}}{2} \quad (9)$$

3.2 Maximum constant boost with third harmonic injection control technique

In order to reduce the cost of the Z-source network, we need to eliminate the low-frequency current ripple by using

a constant shoot-through duty ratio. The maximum constant boost control method is used to achieve maximum voltage boost while maintaining a constant boost viewed from the Z-source network. Third harmonic injection is commonly used in a three-phase inverter system to increase the modulation index range. The third harmonic injection is used here to increase the range of modulation index by which the range of voltage gain increases.

Fig. 4 shows the sketch map of maximum constant boost control with third harmonic injection. There are five modulation curves in this control method, three reference signals and two straight lines V_p and V_n . A third harmonic component with $1/6^{\text{th}}$ of the fundamental component is injected to the three phase voltage references. The upper line V_p is always equal to or higher than the maximum value of the reference signals, and the lower DC line V_n is always equal to or lower than the minimum value of the reference signals. When the carrier wave is greater than the upper line V_p or lower than the lower line V_n , shoot through periods are generated. This control method can have a modulation index from 1 to $2/\sqrt{3}$, the modulation index can be increased to more than 1. This increases the working area of the Z-source inverter. The stress on the devices is reduced in this control strategy.

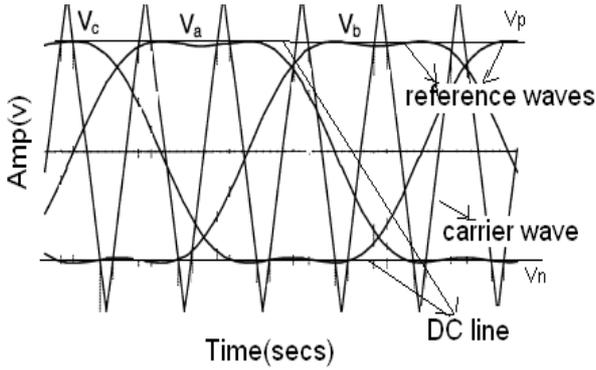


Fig. 4: maximum constant boost controls with Third harmonic Injection Technique

The shoot through duty cycle is given by (9)

$$M = \frac{2}{\sqrt{3}} T_1 / T \quad (10)$$

$$M = \frac{2}{\sqrt{3}} (T - T_0) / T$$

$$T_0 / T = 1 - \sqrt{3} M / 2$$

Equation (10) gives the boost factor of this technique and the voltage gain is given by (11).

$$B = \frac{1}{1 - 2T_0 / T} = \frac{1}{1 - 2(1 - \frac{\sqrt{3}}{2} M)} \quad (11)$$

$$= \frac{1}{\sqrt{3} M - 1}$$

The voltage gain is given by (10)

$$G = \frac{V_{ac}}{V_{in} / 2} = MB = \frac{M}{\sqrt{3} M - 1} \quad (12)$$

III. VOLTAGE STRESS COMPARISON

To examine the voltage stress across the switching device V_{in} is considered to be minimum DC voltage required by the traditional voltage source inverter to obtain the same output voltage. The ratio of the voltage stress to the equivalent DC voltage for the two different control techniques is given by (12), and (13) [10].

$$\frac{V_s}{GV_{in}} = 2 - \frac{1}{G} \quad \text{for simple boost control} \quad (13)$$

$$\frac{V_s}{GV_{dc}} = \sqrt{3} - \frac{1}{G} \quad \text{for max constant boost control} \quad (14)$$

IV. SIMULATION RESULTS

The simulation results of the Z-source inverter with the two different control techniques are discussed in this section. The Z-impedance values L and C are $200\mu\text{H}$ and $400\mu\text{F}$ respectively to obtain 415V, 50Hz AC output for an input voltage range of 200-400V. An RL load of 0.8 PF is used for study. The carrier frequency of the inverter is 10 kHz and the output filter cut-off frequency is 1 kHz.

5.1 Simple boost control Technique

The simulation results of the z-source inverter with the simple boost control technique for an input voltage of 400V are shown in Fig. 5. The Z impedance network boost the voltage to 930V (peak) for a modulation index of 0.72 which is shown in the figure 5(a). The inductor current and capacitor voltage of the Z-network is shown in the figure 5(b) and 5(c) respectively whose values are 32amps (average) and 670V. The inverter output voltage is 415volts, 50Hz which is the rated value.

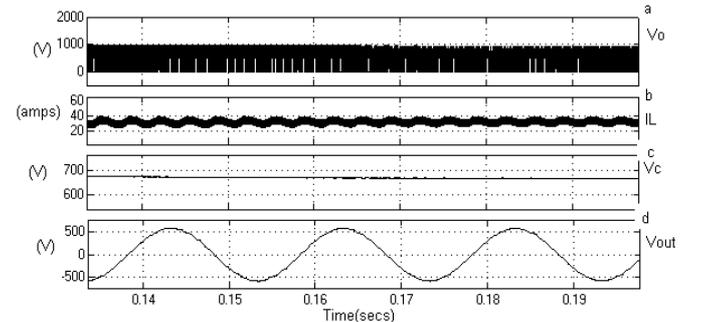


Fig. 5: Z-source inverter output waveforms with simple boost control technique

B. Maximum constant boost with third harmonic injection firing technique

To make a comparative study between the two techniques, simulation is performed using maximum constant boost control with third harmonic injection. In this method, the rated voltage of 415V (rms) is obtained at a modulation index of 0.875. The output waveforms at various stages of the Z-source inverter are shown in Fig. 6. It is observed that the input voltage is boosted to 777V (peak) by the Z-network (Fig. 6(a)). Further it is noted from Fig. 6(b) and 6(c) that the inductor current is 28 Amps (average) and capacitor voltage is 592V.

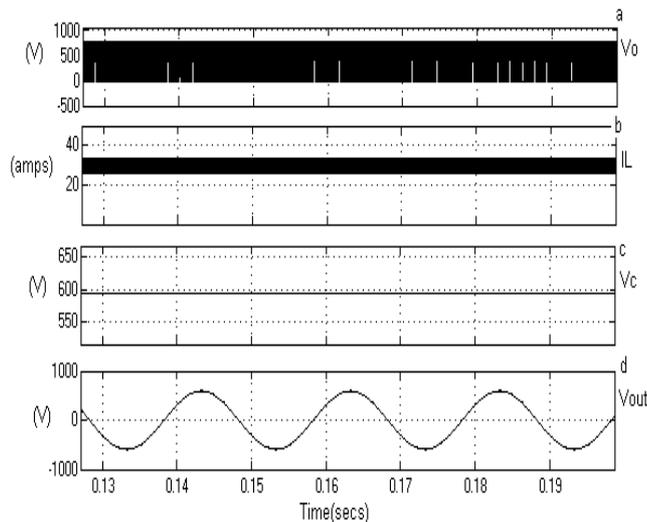


Fig. 6: Z-source inverter output waveforms with maximum constant boost control technique

To study the effect of the two control methods on the various waveforms, simulations are performed and the results are presented below.

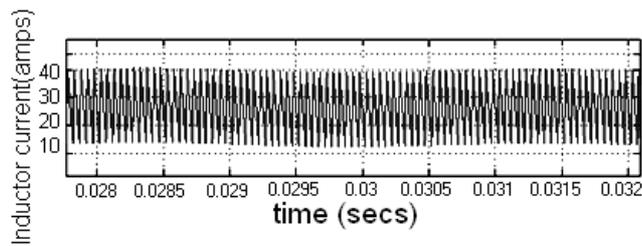


Fig. 7(a): Inductor Current profile of the Z-impedance network with simple boost control scheme

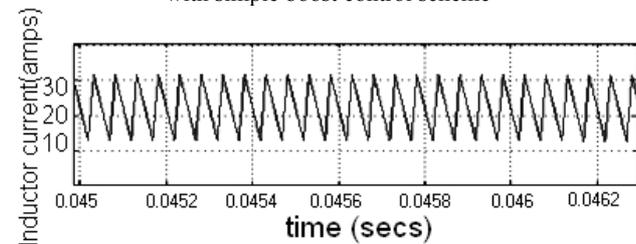


Fig. 7(b): Inductor Current profile of the Z-impedance network with maximum constant boost with third harmonic injection control scheme

Fig. 7(a) and Fig. 7(b) shows the inductor current profile obtained from the Z impedance network by the two different control schemes. It is noted that to obtain the rated voltage, the third harmonic injection scheme takes a 12.5% less inductor current than the simple boost scheme. Thus the inductor rating is reduced by the use of maximum constant boost control with third harmonic injection scheme.

The detailed view of the capacitor voltages obtained from the two control schemes for the rated voltage of 415V is shown in the Figs. 8(a) and 8(b). It is seen that for maximum constant boost control scheme with third harmonic injection the capacitor voltage is 21.5% less compared with simple boost control scheme which reduces the cost of the capacitor used.

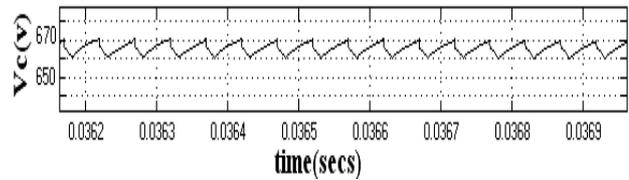


Fig. 8(a); capacitor voltage waveform of the Z-impedance network with simple boost control scheme

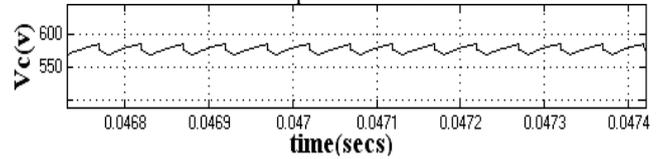


Fig. 8(b): Capacitor voltage waveform of the Z-impedance network with maximum constant boost with third harmonic injection control scheme

The output voltage waveforms without filter obtained from the Z-source inverter by the two control schemes is shown in the Figs. 9(a) and 9(b). For the same output voltage, the peak value of the output voltage with simple boost control is 800V and with that of third harmonic injection it is 632V.

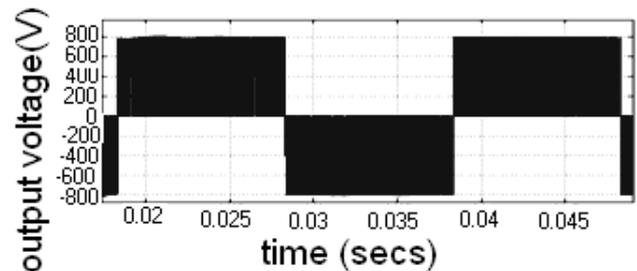


Fig. 9(a): Output voltage waveform of the Z-source inverter without filter for simple boost control scheme

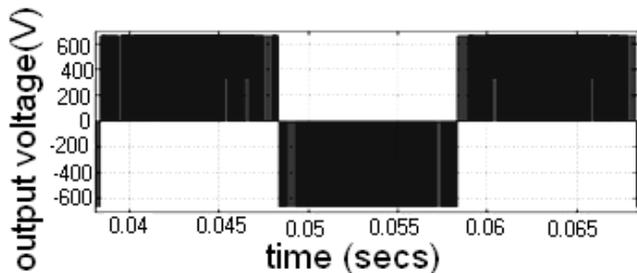


Fig. 9(b): Output voltage waveform of the Z-source inverter without filter for maximum constant boost with third harmonic injection control scheme

To make a study on the ripples present in the output current waveform of the Z-source inverter with the two different control schemes, simulations are performed to obtain the rated voltage. Fig.10(a) shows the output current waveform with simple boost control scheme and Fig.10(b) shows the output current waveform with third harmonic injection scheme. It is found that the current ripple obtained with simple boost control scheme is 9 amps whereas with third harmonic injection scheme it is 5amps. Thus the ripple present in the output current is decreased with third harmonic injection. In addition it is found that for over modulation of 1.2 with third harmonic injection scheme, The output current ripple reduces to 2amps. The reduction in the output current ripple reduces the cost of the filter used in maximum constant control with third harmonic injection scheme.

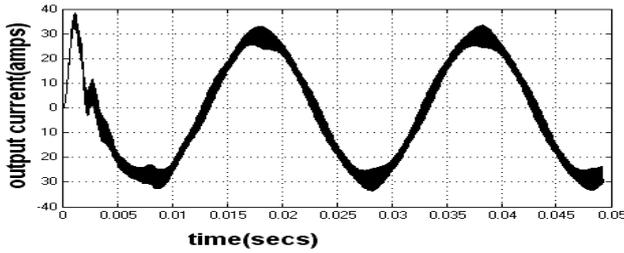


Fig. 10(a): Output current waveform of the Z-source inverter without filter for simple boost control scheme

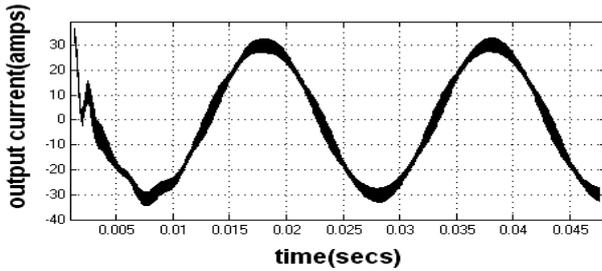


Fig. 10(b): Output current waveform of the Z-source inverter without filter for maximum constant boost with third harmonic injection control scheme

To study the harmonics present in the output voltage waveform, total harmonic distortion is obtained for the two different control schemes. The total harmonic distortion obtained with simple boost control is 3.7% and with that of third harmonic injection is 2.9%.The harmonic profile with both control scheme is shown in the Fig. 11(a)&(b). Thus there is a reduction in the THD with third harmonic injection scheme.

The simulation is repeated for different values of modulation index for the two control methods and the steady state output voltages are presented in Table 1.

Table 1: Comparison of Simulated Output Voltages for the Two Control Techniques, $V_{in}=400V$

Modulation index	Simple boost control		Maximum constant boost control with third harmonic injection	
	Boost factor	V(L-L) rms (v)	Boost factor	V(L-L) rms (v)
1.15	0.762	215	1	282
1	1	255	1.366	320
0.95	1.11	264	1.54	352
0.9	1.25	275	1.79	410
0.85	1.42	303	2.12	430
0.8	1.67	326	2.59	494
0.75	2	384	3.34	597
0.72	2.27	415	4.04	700
0.7	2.5	427	4.7	782

Table 2: Comparison of Boost factor and Modulation index of the Two control Techniques

Input voltage(v)	Modulation index		Boost factor		Output voltage of Z-source inverter(v)
	SB control	MCBTHI control	SB control	MCBTHI control	
400	0.72	0.875	2.34	1.94	415
300	0.64	0.78	3.52	2.89	415
200	0.59	0.7	5.72	4.82	415

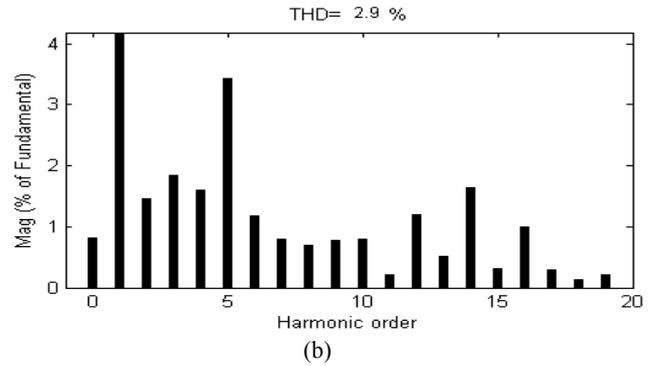
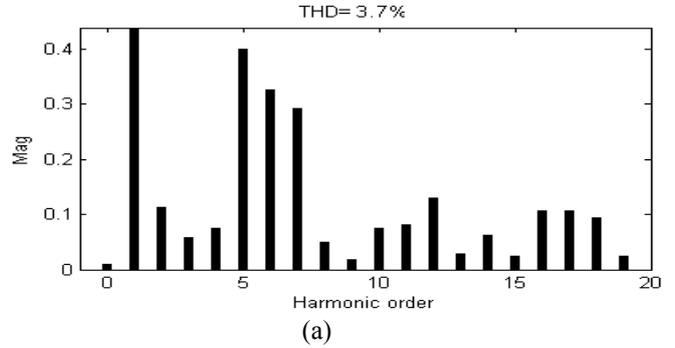


Fig. 11(a) &(b): Total harmonic distortion of the Output voltage waveform of the Z-source inverter with both control schemes

It is seen that, the output voltage increases with decreasing modulation index for both the control techniques. However the rated output is obtained at a higher modulation index in maximum constant boost control with third harmonic injection firing technique.(i.e. with a lower boost factor). As the boost factor is low, the Z impedance network requires low values of L and C. Table 2 shows the modulation index and the corresponding boost factor to obtain the rated output at different input voltages. For low values of input voltage, the shoot through period is increased to increase the boost factor. The range of boost factor is from 2.34 to 5.72 for simple boost control technique whereas it is from 1.94 to 4.82 for maximum constant boost control with third harmonic injection firing technique for an input voltage of 400V to 200V. SB- simple boost

MCBTHI – Maximum constant boost control with third harmonic injection.

The voltage gain and stress on the devices are calculated using equation (7), (11)-(13) with different modulation index for the above mentioned control techniques at 400V input. Fig. 12 shows the variation of voltage gain with modulation index.

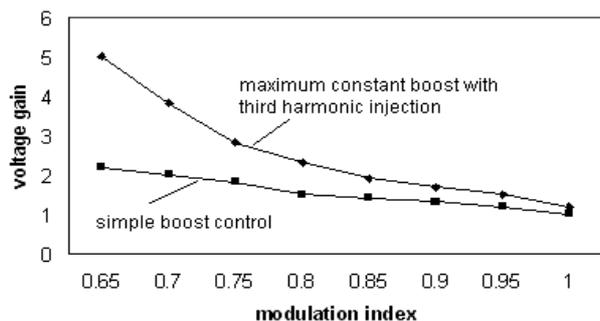


Fig. 12: Effect of modulation index on voltage gain for two control techniques

It is seen that the voltage gain is high for maximum constant boost with third harmonic injection technique. For a modulation index of 0.65, the voltage gain is 60% high compared to simple boost control technique. The difference in voltage gain decreases as the modulation index increases and they tend to be equal for modulation index greater than 1.

Fig. 13 shows the variation of voltage stress with the voltage gain.

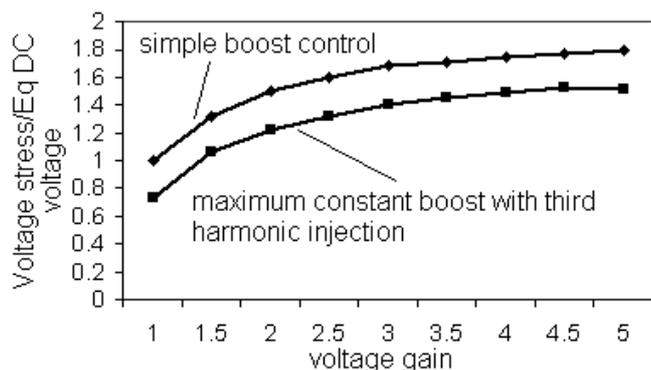


Fig. 13: Comparison of voltage stress for two control techniques

It is observed that the voltage stress developed by the maximum constant boost control with third harmonic injection is about 20% less compared to the simple boost control for the range of modulation index from 0.65 to 1.15. Therefore the maximum constant boost with third harmonic injection technique is advantageous due to the reduced voltage stress and increased voltage gain.

V. EXPERIMENTAL RESULTS

A single phase Z-source inverter with maximum boost control with third harmonic injection is implemented in hardware and is shown in Fig.14. A PIC microcontroller and a PWM generator is used to generate the firing pulse with the shoot through states. The Z-parameters used in Z-source inverter for the hardware setup are $L=3\text{mH}$, 5A and $C=470\ \mu\text{F}$, 600V . The firing pulses generated and given to the gate circuit of Z-source inverter is shown in Fig. 15. The capacitor voltage and DC link voltage for $V_{in}=40\text{V}$ are 60V and 104V for a shoot through period of 0.214ms . The waveforms are shown in Fig. 16 and Fig. 17. The output voltage of Z-source inverter for the input of 40V at zero shoot through state and the 1.2ms shoot through period are 24V(peak) and 100V(peak) , $V_{rms}=72\text{V}$. The output

waveforms are shown in Fig. 18. The effect of shoot through period is studied and the steady state results are presented in Fig. 19.

It is seen that the output voltage increases as the shoot through period is increased and reaches a maximum of 100v(peak) volts at shoot through period of 0.214msec . It is further seen that the experimental results closely matches with the simulation results.

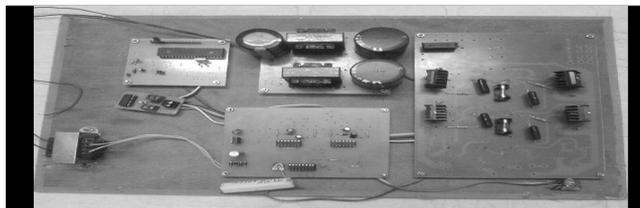


Fig. 14: Prototype Z-Source inverter

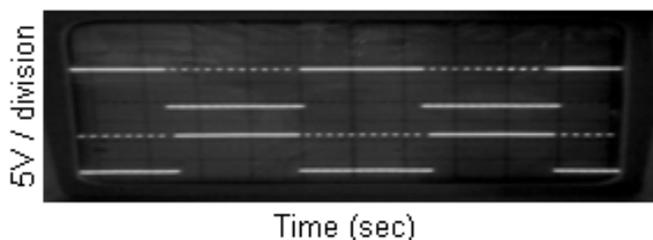


Fig. 15: Firing pulse of Z-source inverter.

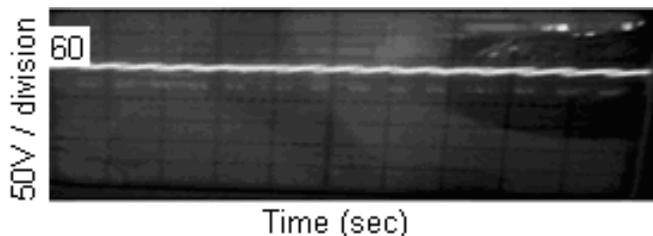


Fig. 16: Capacitor voltage of Z-source inverter.

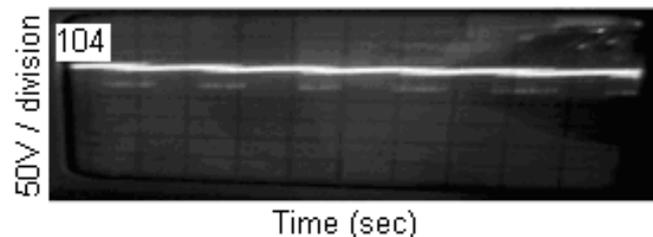


Fig. 17: DC link voltage of Z-source inverter.

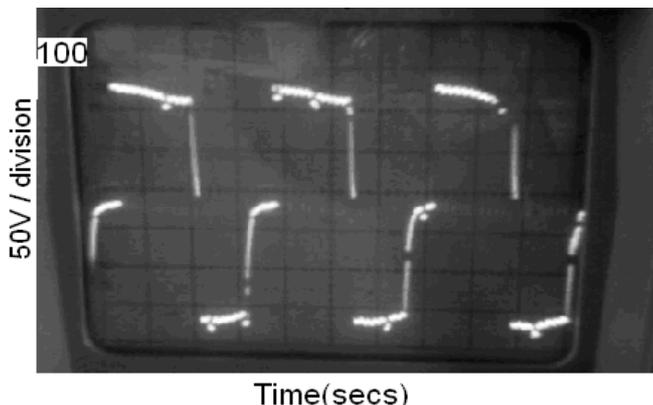


Fig. 18: Output voltage waveform of Z-source inverter.

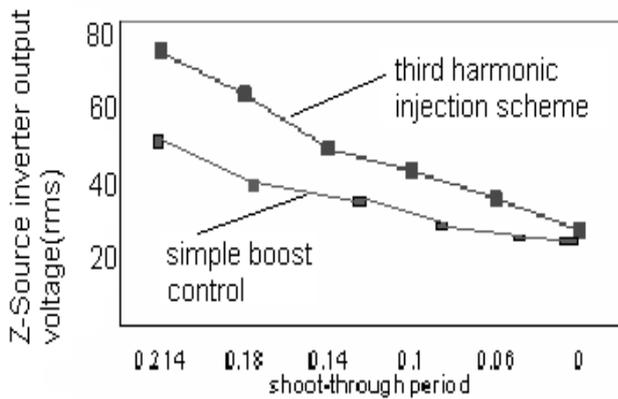


Fig. 19: Effect of shoot through period on Z-inverter output voltage for both the control schemes obtained in hardware.

VI. CONCLUSION

A simulation model of the Z-source inverter with two different control schemes namely the simple boost control and maximum constant boost with third harmonic injection control are presented. The performance of the inverter is analyzed with the two firing schemes. Based on the simulation results, it is found that the maximum constant boost with third harmonic injection technique provides the required output voltage at a low boost factor of approximately 18% less than simple boost control. The inductor current and the capacitor voltage are reduced with third harmonic injection for the same output voltage resulting in reduced L and C ratings of the Z-network. The output current ripple is also reduced by 1.8 times thus lessens the filter components used. Further, with this technique the voltage stress on the device is considerably reduced. Therefore the maximum constant boost control with third harmonic injection is identified to be the better scheme in terms of L and C requirements, voltage gain and voltage stress and implemented in hardware. The experimental results closely match with the simulation results thus validating the simulation model.

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BIOGRAPHIES

T. Meenakshi received her Bachelor of Engineering in Electrical & Electronics from Madras University in 2000 and Master of Technology in Electric Drives and Control from Pondicherry University in 2008. Currently she is working as Assistant professor in the department of Electronics and Communication Engineering in IFET college of Engineering, Villupuram, India. She has published papers in national and international conferences and her areas of Interest include renewable energy systems, power converters and drives.

K. Rajambal received her Bachelor of Engineering in Electrical & Electronics, Master of Engineering in power electronics and Ph.D in Wind Energy Systems in 1991, 1993 and 2005 respectively from Anna University, Chennai, India. She is working as a Assistant professor in the Department of Electrical and Electronics in Pondicherry Engineering College, Pondicherry, India. Her area of interest includes in the fields of wind energy systems and power converter with soft switching PWM schemes.