Advanced Pulse Width Modulation Techniques for Z Source Multi Level Inverter

B. M. Manjunatha, D. V. Ashok Kumar, M. Vijay Kumar

***Abstract*—**This paper proposes five level diode clamped Z source Inverter. The existing PWM techniques used for ZSI are restricted for two level. The two level Z Source Inverter have high harmonic distortions which effects the performance of the grid connected PV system. To improve the performance of the system the number of voltage levels in the output waveform need to be increased. This paper presents comparative analysis of a five level diode clamped Z source Inverter with different carrier based Modified Pulse Width Modulation techniques. The parameters considered for comparison are output voltage, voltage gain, voltage stress across switch and total harmonic distortion when powered by same DC supply. Analytical results are verified using MATLAB.

***Keywords*—**Diode Clamped, Pulse Width Modulation, total harmonic distortion, Z Source Inverter.

I. Introduction

A wide research has taken place on two level Z Source Inverters [ZSI] in the past few years. The ZSI has the advantages of performing buck and boost operations and required conversion is achieved in a single stage. The drawback of conventional voltage source inverter is two switches in the same leg should not be gated on simultaneously. This state of operation is hailed in ZSI which is called as shoot through state. By applying shoot through state the output voltage of the inverter is boosted which improves the reliability of inverter. This property of ZSI is considered favorable for PV system [1] where available DC voltage is less & varying in magnitude.

The two level ZSI is shown in Fig. 1. On DC side of ZSI, a diode D and impedance network connected in "X" shape, composed of two inductors L_1 and L_2 & two capacitors C_1 and C_2 [2]. This Z circuit couples the inverter circuit to the power source which allows the single stage conversion.

The buck boost operation of ZSI depends on boost factor. To get a boost factor null state are reimbursed with shoot through state without disturbing the active states [2]. For placing shoot through states, the PWM methods that is simple boost, maximum constant boost and maximum constant are used as explained in [3], [4].

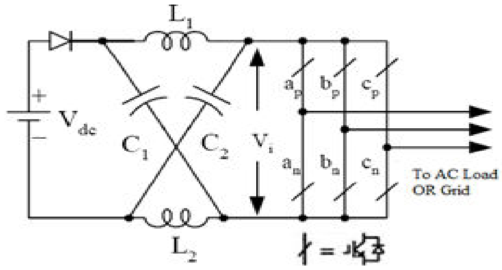

Fig. 1 Two level Z Source Inverter

In simple boost method, two constant reference signals are used in addition to sinusoidal reference signal for inserting shoot through states. In maximum boost method, two sine wave envelopes are used to produce shoot through states. In maximum constant boost, sine waves with an offset value varying around peak value of reference sine wave are used to generate shoot through pulses.

The fore mentioned PWM techniques uses only one carrier wave for generating gate pulses which restricts the output voltage of the ZSI to two level only. Due to this the Total Harmonic Distortions [THD] in the output voltage increases. To increase the output voltage magnitude the shoot through period need to be increased, which leads to increase in voltage stress across the switches. To overcome these difficulties, the output voltage level of ZSI is increased by using diode clamped multi level inverter topology. The number of levels in the output voltage is increased by taking (m-1) carriers, where m stands for number of levels in the output voltage.

In this paper, five level diode clamped Z Source inverter is simulated using various multi carrier PWM techniques [5], [6]. The performance of ZSI is evaluated by considering output voltage, voltage gain and voltage stress across switch and THD.

II. Impedance Type Inverter

The Conventional Inverter will operate in two states: active state & null state. In ZSI along with active state & null State, the third state i.e., shoot through state is allowed. In six active states and in zero-state (null state) mode, the ZSI operates as conventional inverter. In the shoot-through state, all the switches in one or more legs are turned on. The operating states of conventional inverter & ZSI are explained in Fig. 2. Null states are represented as "0" & shoot through state is represented as "1". From Fig. 2, It is observed that shoot through states are inserted in the null states without disturbing

B. M. Manjunatha is with the Department of Electrical & Electronics Engineering of Rajeev Gandhi Memorial college of Engineering and Technology, Nandyal, Andhra Pradesh, India (phone: +91-9441085422; e-mail: manjunath.bmeee@gmail.com.

D. V. Ashok Kumar is with the Electrical and Electronics Engineering Department & Principal of Syamala Devi Institute of Technology for women, Nandyal, Andhra Pradesh, India (e-mail: principal.sdit@gmail.com).

M. Vijay Kumar is Professor in Electrical Engineering Department & Director of admissions, Jawaharlal Nehru Technological University Anantapur, Anantapur, Andhra Pradesh, India (e-mail: mvk_2004@rediffmail.com).

the active states. By controlling the shoot through duration the DC link voltage is varied, which in turn modifies the output voltage magnitude to any desired value [7], [8].

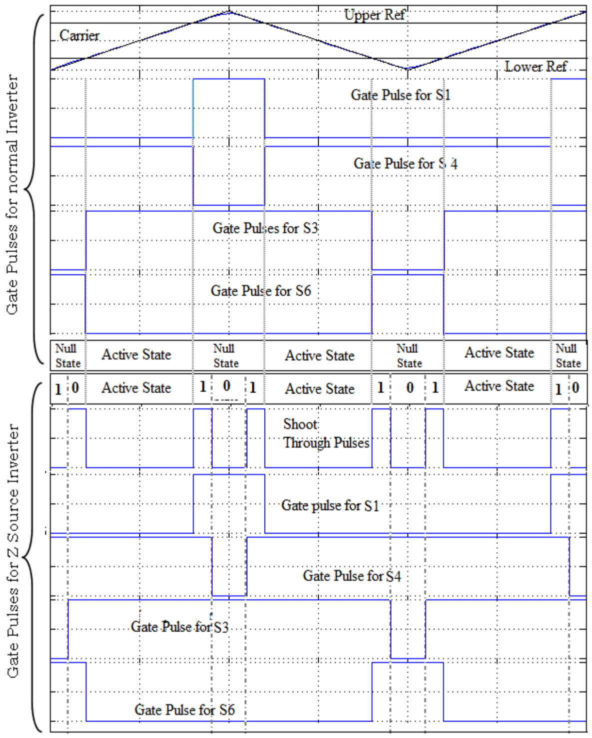

Fig. 2 Generation of Switching pulses to Conventional & ZSI

The equivalent circuit of ZSI's operating in null, active & shoot through states are shown in Figs. 3, 4 & 5 respectively.

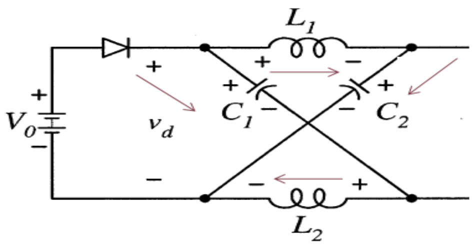

Fig. 3 ZSI Equivalent circuit in null sates

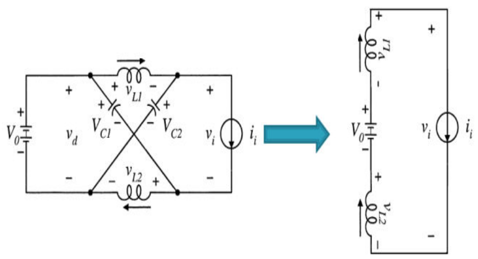

Fig. 4 Equivalent circuit in active states

The Equivalent circuit of ZSI in active states is shown in Fig. 4. In this state the inverter will operate as normal inverter but the input voltage to the inverter is boosted. The magnitude of boost depends on shoot through duty ratio.

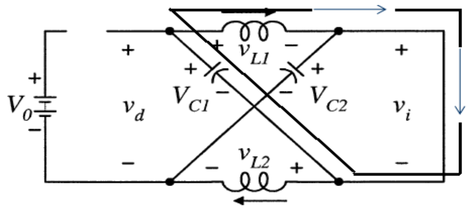

Fig. 5 Equivalent circuit in shoot through state

When circuit is in a shoot through state, the summation of the two capacitors voltage is greater than input DC voltage ($V_{C1}+V_{C2} > V_0$), will appears across the diode. Thus diode is reverse biased, and the capacitors charge the inductors. The voltage across both the inductors are: $V_{L1} = V_{C1}$ & $V_{L2} = V_{C2}$. The five level Diode clamped Z source inverter is shown in Fig. 6. This inverter configuration is selected based on the following constraints, (M-1) sources, 2(M-1) switching devices, (M-1) (M-2) clamping diodes for each leg, where M stands for number of level in the output voltage. In this paper a five level ZSI is simulated which requires 4 DC source of same value, 8 switching Device & 12 clamping diodes.

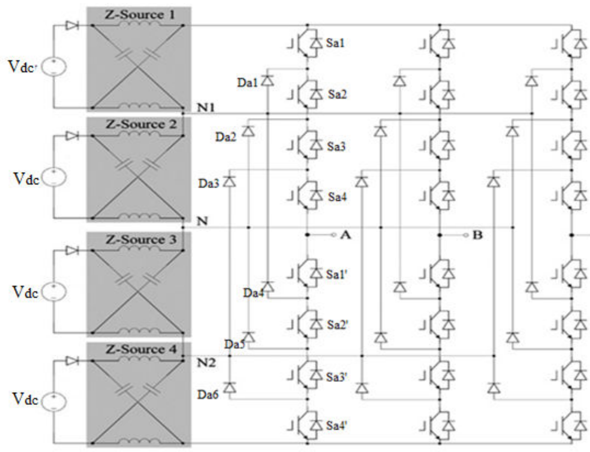

Fig. 6 Z source based five level Inverter

To generate shoot through state one of the following switching combination is used.

- ✓ To get complete shoot through state, the Switches S_{a1}, S_{a2}, S_{a3}, S_{a4}, S_{a1}^1, S_{a2}^1, S_{a3}^1 & S_{a4}^1 are turned on.
- ✓ To get shoot through state in Z source 1 alone, the switches S_{a1}, S_{a2}, S_{a3}, S_{a4}, S_{a1}^1 & D_{a4} are turned on.
- ✓ To get shoot through period in Z source 2 alone, the switches D_{a1}, S_{a2}, S_{a3}, S_{a4}, S_{a1}^1 S_{a2}^1 & D_{a5} are turned on
- ✓ To get shoot through period in Z source 3 alone, the switches D_{a2}, S_{a3}, S_{a4}, S_{a1}^1 S_{a2}^1 S_{a3}^1 & D_{a6} are turned on
- ✓ To introduce shoot through period in Z source 4 alone, the switches D_{a3}, S_{a4}, S_{a1}^1, S_{a2}^1, S_{a3}^1 & S_{a4}^1 are turned on
- ✓ To get upper shoot through state (ZSI1 & ZSI2), the switches S_{a1}, S_{a2}, S_{a3} and S_{a4} are turned on

- ✓ To get lower shoot through state (ZSI3 & ZSI4), the switches S_{a1}^1, S_{a2}^1, S_{a3}^1 & S_{a4}^1 are turned on.

III. PWM Techniques for Z Source Diode Clamped Multilevel Inverter

A. Simple Boost Method

This method uses two straight lines of equal magnitude with opposite polarities are used shown in Fig. 7 as +K & -K. To insert shoot through state the magnitude of carrier wave must be greater than the carrier. In this method all carriers are in phase opposition with the neighbor carriers & it is called as Alternate Phase Opposition Disposition (APOD). When the carrier waveform is greater than the upper constant, or lower than the bottom constant line the circuit goes into shoot through state. Otherwise it operates as a conventional carrier based PWM. This method is very simple. The voltage stress across the switches is high since a few conventional zero states are not utilized. The theoretical values of modulation index, shoot through duty ratio, boost factor, output peak ac voltage & voltage across capacitors is obtained by:

$$\text{Modulation Index} = m_a = \frac{A_m}{\frac{(m-1)}{2} * A_c} \quad (1)$$

$$\text{Shoot through Duty Ratio} = D_o = (1 - m_a) \quad (2)$$

$$\text{Boost Factor} = B = \frac{1}{1-D_o} \quad (3)$$

The phase output peak voltage is given by

$$V_{ac} = m_a * B * \frac{V_{dc}}{2} \quad (4)$$

Voltage across capacitor V_c is given by

$$V_c = \frac{1-D_o}{1-2D_o} * V_{dc} \quad (5)$$

B. Maximum Constant Boost Method

Fig. 8 shows the implementation of maximum constant boost control method. By using this method one can achieve the maximum voltage gain & keeps the shoot-through duty ratio constant. In this control technique five modulation curves are used out of which three are reference signals and other two are shoot-through sine waves with an offset value varying around peak value of reference sine wave shown as +K & -K in Fig. 8. Here all the carrier wave forms are in phase. This type of carrier distribution is called as Phase Disposition (PD). When the carrier triangle wave is greater than the upper shoot-through envelope or lower than bottom shoot-through envelope the inverter is turned into a shoot through state. In between states the inverter will operate as traditional inverter.

$$\text{Modulation Index} = m_a = \frac{A_m}{\frac{(m-1)}{2} * A_c} \quad (6)$$

$$\text{Shoot through Duty Ratio} = D_o = (1 - \frac{\sqrt{3} * m_a}{2}) \quad (7)$$

$$\text{Boost Factor} = B = \frac{1}{\sqrt{3} m_a - 1} \quad (8)$$

The phase output peak voltage is given by

$$V_{ac} = m_a * B * \frac{V_{dc}}{2} \quad (9)$$

Voltage across capacitor V_c is given by

$$V_c = \frac{2}{\sqrt{3}} \frac{1-D_o}{1-2D_o} * V_{dc} \quad (10)$$

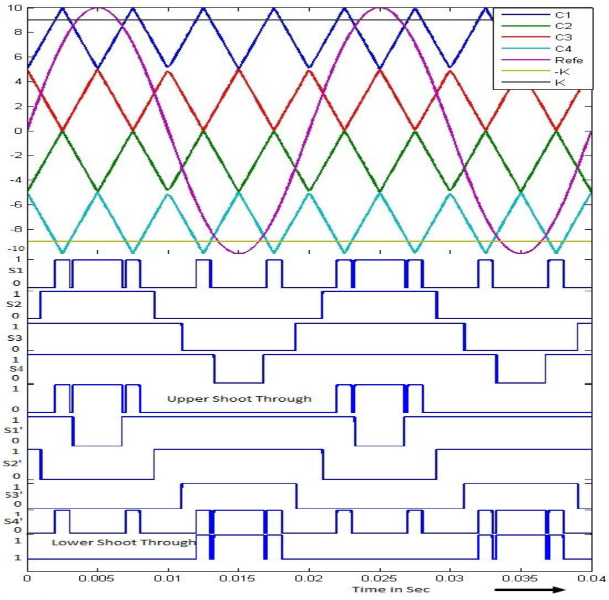

Fig. 7 Simple Boost Method with APOD

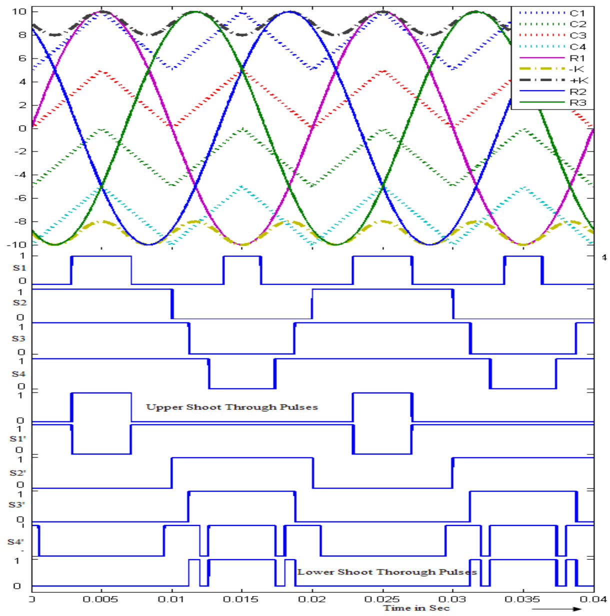

Fig. 8 Maximum constant Boost method with PD

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C. Maximum Boost Method

Fig. 9 shows the implementation of maximum boost control strategy. In this control method, the six active states are unchanged and turn all zero states into shoot-through states. Thus maximum shoot through time interval, maximum Boost Factor and maximum voltage gain are obtained for any given modulation index M without distorting the output waveforms. It can be seen from Fig. 9 that, circuit is in shoot-through state when the carrier wave is either larger than the maximum value of the references or lesser than the minimum of the references. All carrier waveforms above the zero reference are in phase and are out of phase with those below zero reference by 180°. This type of carrier distribution is called as Phase Opposition Disposition (POD).

$$\text{Modulation Index} = m_a = \frac{A_m}{\frac{(m-1)}{2} * A_c} \quad (11)$$

$$\text{Shoot through Duty Ratio} = D_o = \frac{2\pi - 3\sqrt{3} m_a}{2\pi} \quad (12)$$

$$\text{Boost Factor} = B = \frac{\pi}{3\sqrt{3} m_a - \pi} \quad (13)$$

The phase output peak voltage is given by

$$V_{ac} = m_a * B * \frac{V_{dc}}{2} \quad (14)$$

Voltage across capacitor V_c is given by

$$V_c = \frac{2*\pi}{3\sqrt{3}} \frac{1-D_o}{1-2D_o} * V_{dc} \quad (15)$$

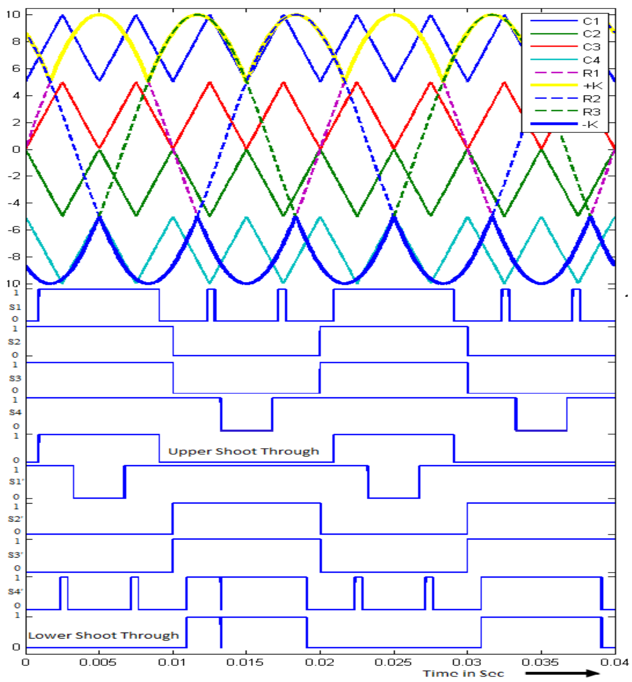

Fig. 9 Maximum Boost PWM technique with POD

IV. Theoretical Analysis

Fig. 10 shows the voltage gain versus boost factor B of a Z-source inverter for all fore mentioned control methods. From Fig. 10, it can be concluded that for any boost factor, the maximum boost control method has higher voltage gain when compared to simple boost method & slightly higher voltage gain than the maximum constant boost control method.

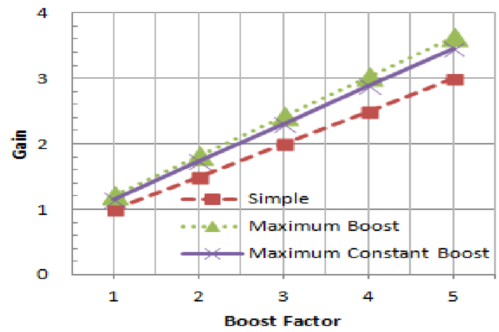

Fig. 10 Voltage gain Vs boost factor for different control method

The voltage stress across the switching device for obtaining same voltage gain with different control methods is shown in Fig. 11. From this figure, it can be concluded that the maximum boost control method will reduces the voltage stress across the switches when compared to simple & maximum constant boost control methods.

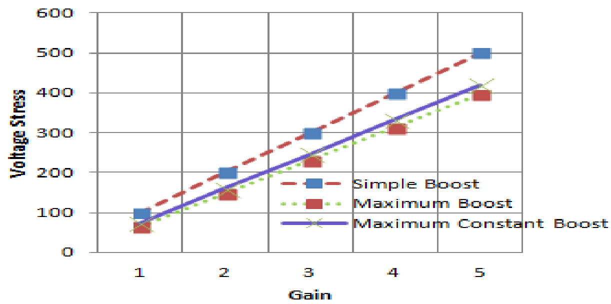

Fig. 11 Voltage stress Vs gain for different control method

Fig. 12 shows the voltage gains as a function of shoot through duty ratio for all three control methods.

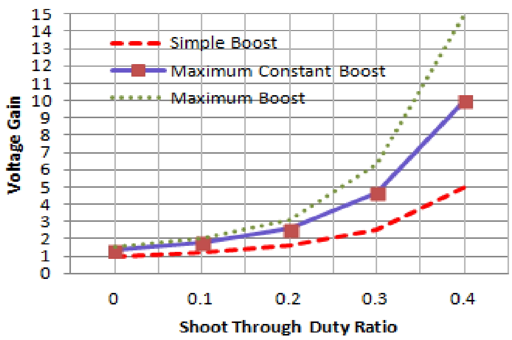

Fig. 12 Voltage gain Vs shoot through Duty Ratio for different control method

From Fig. 12, it can be concluded that maximum boost control method will have high voltage gain when compared to other methods for same shoot through duty ratio. From Figs. 10-12, it is clear that ZSI with maximum boost control technique gives better performance.

V. Simulation Results

To study the performance of Z source inverter, simulations were performed in MATLAB/SIMULINK.

A. Three Level Z Source Inverter

The boost factor B is taken as 2 for comparing voltage gain, Fundamental voltage & THD of ZSI with different control methods. The parameters considered for the simulation are as follows: the input dc voltage source is V_o=400 V, inductor $L_1 = L_2$ = 3.3m H and capacitor $C_1 = C_2$ =500μ F, the switching frequency is considered as 10 kHz. Fig. 13 to 15 shows output line to line voltage of ZSI for all three methods with phase disposition carrier

For archiving the boost factor of 2, the modulation index & voltage gain is calculated as follows for simple boost method

$$\text{Modulation Index (M)} = \frac{B+1}{2B} = 0.75 \qquad (16)$$

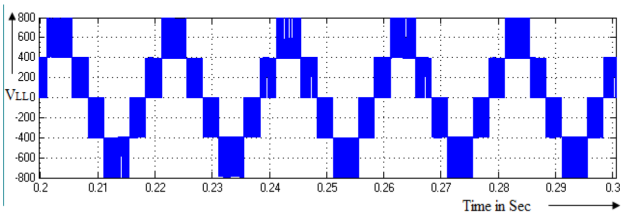

Fig. 13 Line to Line voltage of three level ZSI with simple boost technique

The modulation index & voltage gain for maximum constant boost technique is calculated as follows, for getting a boost factor of 2

$$\text{Modulation Index (M)} = \frac{B+1}{\sqrt{3}B} = 0.866 \qquad (17)$$

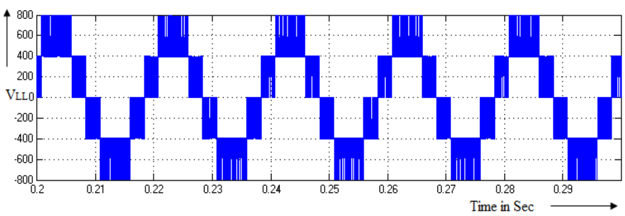

Fig. 14 Line to Line voltage of three level ZSI with maximum constant boost technique

Modulation index & voltage gain of ZSI with maximum boost technique is calculated as

$$\text{Modulation Index (M)} = \frac{(B+1)*\pi}{3\sqrt{3}B} = 0.906 \qquad (18)$$

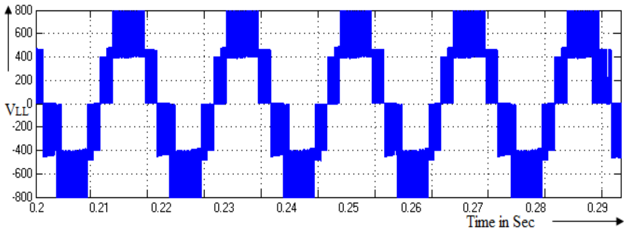

Fig. 15 Line to Line voltage of three level ZSI with maximum boost technique

Table I shows the simulated values of fundamental voltage and its corresponding THD with different boosting techniques used for ZSI to obtain boost factor of 2.

TABLE I
COMPARISON TABLE FOR THREE LEVEL Z SOURCE INVERTER

Boosting Technique	Modulation index	Type of Carrier	Fundamental voltage	% of THD
Simple Boost	0.75	PD	516	42.32
		POD	504	73.4
Maximum constant Boost	0.866	PD	572.6	40.73
		POD	567	61.69
Maximum Boost	0.906	PD	669	39.50
		POD	647	52.10

From Table I it is clear that system is giving better performance with Phase disposition carrier when compared to phase opposition disposition carrier.

B. Five level Z Source Inverter

For comparing the performance of five level ZSI, the modulation index is selected as 1. For this modulation index the fundamental output voltage, boost factor, THD & voltage gain are compared with all boosting technique and with different carriers. In simple boost method, if shoot through modulation index is one, there is no boost (B=1) in the output voltage & hence ZSI will operate as normal inverter. Line to Line voltage of simple boost method is shown in Fig. 16. In maximum constant boost control method with modulation index of one, then boost factor will be 1.362. The Line to Line voltage of maximum constant boost method is shown in Fig. 17. Finally for maximum boost control with modulation index one, boost factor will be 1.529. Figs. 16-18 show output line to line voltage of ZSI for all three methods with phase disposition carrier & comparison of results are shown in Table II.

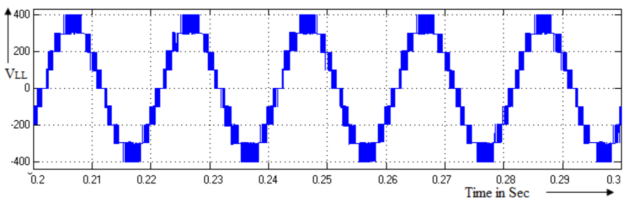

Fig. 16 Line to Line voltage of five level ZSI with simple boost technique

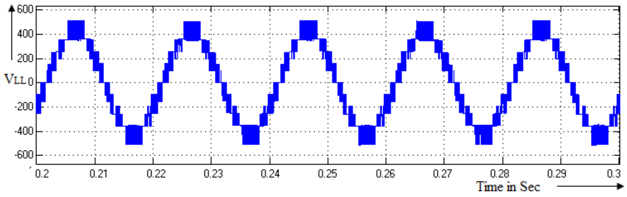

Fig. 17 Line to Line voltage of five level ZSI with maximum constant boost technique

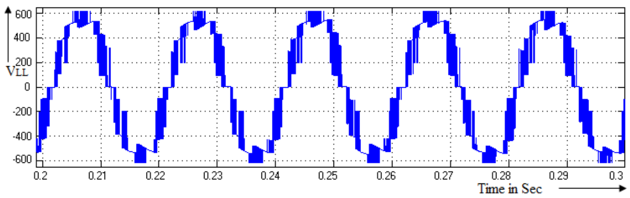

Fig. 18 Line to Line voltage of five level ZSI with maximum boost technique

TABLE II
COMPARISON TABLE FOR FIVE LEVEL Z SOURCE INVERTERS

Boosting Technique	Type of Carrier	Fundamental voltage	% of THD	Voltage Stress across the switch in Volts
Simple Boost	PD	347.7	15.51	100
	POD	344.7	19.2	100
	APOD	344.3	21.48	100
Maximum constant Boost	PD	426.5	18.25	100
	POD	430.4	24.17	102
	APOD	430.1	27.5	103
Maximum Boost	PD	597.8	19.28	107
	POD	566.4	22.03	105
	APOD	569.9	29.93	110

From Table II it is clear that system is giving better performance with Phase disposition carrier when compared to phase opposition disposition & Alternate Phase opposition disposition carrier.

VI. CONCLUSION

This paper investigates the voltage gain, THD and voltage stress with three major types of boosting techniques used for ZSI using MATLAB/SIMULINK software. Based on the availability of input & requirement of load, proper control method is chosen. THD is controlled by increasing the number of levels in the output voltage. Simple boost method is easy for the implementation but available output voltage is limited and voltage stress across the switches increases. Maximum boost method will have good voltage gain and voltage stress across the switches is reduced when compare to simple & maximum constant boost method.

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