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MODIFIED PWM CONTROL METHODS OF Z SOURCE INVERTER FOR DRIVE APPLICATIONS

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ABSTRACT

This paper deals with comparative analysis different modified PWM control methods of Z source inverter (ZSI), also known as impedance source inverter for adjustable speed drives. In order to obtain boosted output voltage, a shoot through state should be created followed by an active state. Therefore, small changes are made in the classical three phase sinusoidal Pulse Width Modulation (PWM) technique to provide various shoot through control strategies for the ZSI. Simple boost control with triangular carrier wave, simple boost control with sinusoidal carrier wave, maximum boost control, maximum boost control with third harmonic injection, constant boost control and constant boost control with third harmonic injection are available in the literature for applications. In this work, simulations of various shoot through control methods are performed for the same modulation index and design parameters of the ZSI. The output voltage and output current of the inverter for the same input and load conditions are analysed using MATLAB/SIMULINK.

Keywords: z-source inverter, pulse width modulation, boost factor, modulation index, shoot through.

1. INTRODUCTION

Adjustable speed drives (ASDs), also known as Variable Speed Drives (VSDs) are used for different applications in industry. An ASD is usually based on a Voltage Source Inverter (VSI) as shown in Figure-1a. The traditional VSI can provide only buck output voltage and it cannot exceed the dc link voltage. Both upper and lower devices of each phase leg cannot be turned on at the same time. Otherwise shoot through would occur and the devices will be destroyed [1]-[3]. The recently developed inverter known as Z source inverter has an ability to overcome the previously mentioned issues. Z Source Inverter (ZSI) employs a unique impedance network to couple the converter to the source [4]. It is used for both buck and boost operation of inverter. ZSI is used in various applications other than industrial drives like uninterruptable power supplies [5], hybrid electric vehicles [6] and residential photovoltaic systems [7]. Boosted output voltage is obtained with the proper insertion of shoot through state followed by the active states. Several modified PWM techniques are used to control the ZSI.

In this work, different boost control methods for ZSI fed motor drives are analysed and discussed. Section II explains the Z Source Inverter topology. Section III presents the principle of operation of ZSI. Analysis of ZSI is explained in section IV. Various PWM control methods are discussed in section V. Results and discussions are given in section VI. Comparison of various PWM control methods are discussed in section VII. Section VIII concludes the paper.

II. Z SOURCE INVERTER TOPOLOGY

The Z Source Inverter (ZSI) rectifies the problems associated with the voltage source and current source inverters. Figure-1b replaces the VSI with ZSI fed motor drive [4].

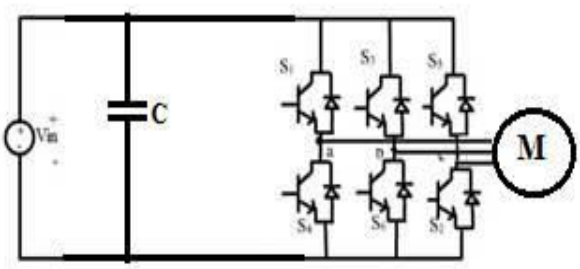

Figure-1(a). Traditional VSI fed motor drive.

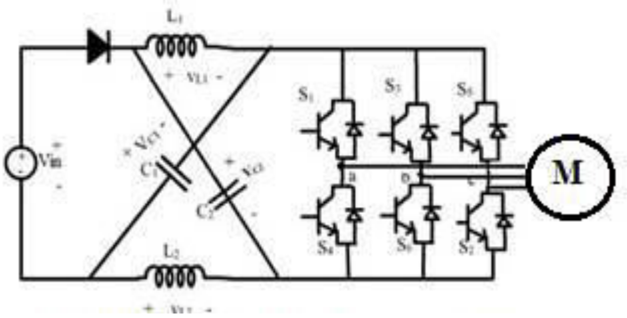

Figure-1(b). Z source inverter fed motor drive.

The symmetrical impedance network connects the source to the load through the inverter. The impedance network consists of two inductors and two capacitors. The values of both inductors and capacitors are equal. Shoot through can no longer destroys the device and the reliability of the inverter is high.

III. OPERATION OF ZSI

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The classical inverters such as voltage source inverter and current source inverter, has eight permissible switching states. Among these eight permissible states, six of them are active states during which the dc voltage appears across the load terminals. During zero states, the load terminals are shorted through either upper or lower three devices. Z-source inverter has nine permissible switching states. Eight of them are similar to the traditional inverters. But Z-source inverter has an extra zero state which is known as shoot-through zero state during which the load terminals are shorted through both the lower and upper devices of any one phase leg, any two phase legs, or all three phase legs.

The ZSI has two operating modes: non shoot through state and shoot through state, as shown in Figure-2a and Figure-2b. During the non shoot through state, input diode turns on, and the dc voltage and the energy stored in the inductors are transferred to the load and charge the capacitors. During shoot through state the capacitors discharge to the inductors and to the load. The expression for capacitor voltage, the dc link voltage and the output ac peak phase voltage of ZSI in steady state are given as follows [4].

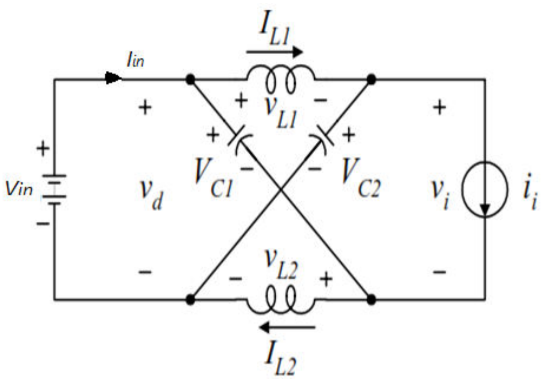

Figure-2(a). Non shoot through mode

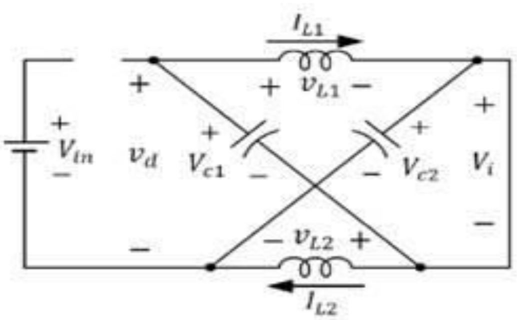

Figure-2(b). Shoot through mode.

IV. ANALYSIS OF ZSI [4]

From the symmetry of the network,

$$V_{C_1} = V_{C_2} = V_C \; ; \; V_{L_1} = V_{L_2} = V_L$$

During shoot through mode for an interval of T_0, as given in Figure-2b,

$$V_L = V_c = L\frac{di}{dt} \tag{1}$$

$$V_i = 0 \tag{2}$$

$$V_d = 2V_c \tag{3}$$

During non shoot through state for an interval of T_1 as shown in Figure-2a,

$$V_L = V_{in} - V_c \tag{4}$$

$$V_{in} = V_d \tag{5}$$

$$V_i = 2V_c - V_{in}. \tag{6}$$

Average value of an inductor during one switching cycle ($T = T_0 + T_1$) is equal to zero.

$$V_L = \frac{T_0 V_c + T_1(V_{in} - V_c)}{T}. \tag{7}$$

$$\frac{V_c}{V_{in}} = \frac{T_1}{(T_1 - T_0)} \tag{8}$$

$$\frac{V_c}{V_{in}} = \frac{1 - \frac{T_0}{T}}{1 - \frac{2T_0}{T}} \tag{9}$$

Peak DC link voltage across the inverter bridge is given as,

$$V_i = \frac{T}{T_0 - T_1} V_{in} = V_c = BV_{in} \tag{10}$$

where B is the boost factor.

$$B = \frac{T}{T_1 - T_0} \geq 1 \tag{11}$$

$$V_{ac} = M\frac{V_i}{2} = MB\frac{Vin}{2} \tag{12}$$

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where M is the modulation index.

$$\frac{V_{ac}}{\frac{V_{in}}{2}} = MB \tag{13}$$

where V_{ac} is the peak output phase voltage.

The capacitor voltage can be expressed as,

$$V_{c_1} = V_{c_2} = V_c = \frac{1-\frac{T_0}{T}}{1-\frac{2T_0}{T}} V_0 \tag{14}$$

V. PWM CONTROL METHODS OF ZSI

Various Sinusoidal Pulse Width Modulation (SPWM) schemes can be applied to the ZSI and their input-output relationship is still hold. Minor modifications in SPWM techniques can provide shoot through pulses for ZSI [8]. Different PWM methods used to control ZSI are as follows:

a) Simple Boost Control (SBC) with triangular carrier PWM
b) SBC with sine carrier PWM
c) Maximum boost control and Maximum boost control with third harmonic injection
d) Constant boost control and Maximum constant boost control
e) Traditional space vector PWM (SVPWM) control

a) SBC with triangular carrier PWM [4]

In this technique, firing pulses are generated by comparing three sinusoidal reference signals and two constant voltage envelopes with the triangular carrier wave. The sinusoidal reference signals are phase displaced by 120 degree and the amplitude of two envelopes is equal to the peak amplitude of reference signals. When the magnitude of the triangular carrier wave is greater than or equal to the positive envelope (or) lower than or equal to the negative envelope, shoot through pulses are generated and they control the shoot through duty ratio [4]-[8]. The reference sinusoidal voltage signals along with the triangular carrier wave and two constant DC voltages are shown in Figure-3a.

The pulses produced using this method are shown in Figure-3b. For a complete switching period T_s, T_0 is the zero state time periods and D_0 is the shoot-through duty ratio $(D_0) = \frac{T_0}{T_s}$

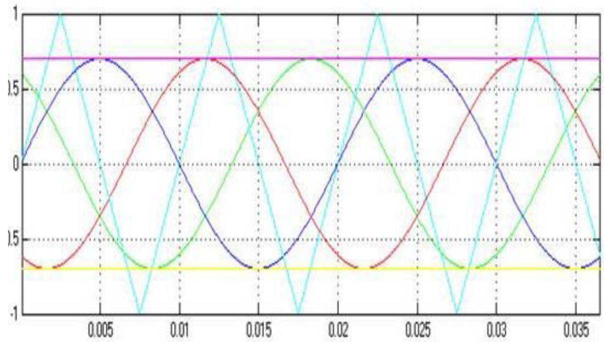

Figure-3(a). Illustration of SBC with triangular carrier PWM.

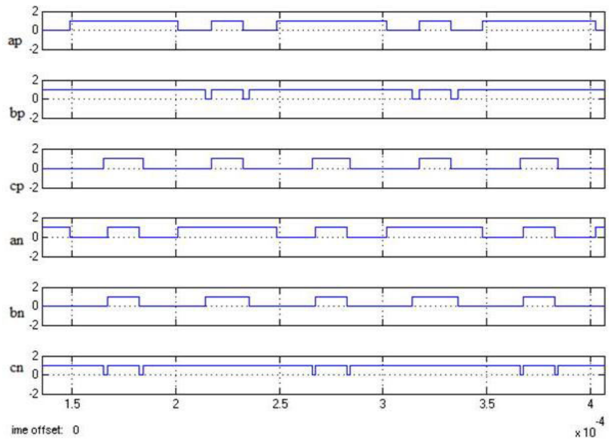

Figure-3(b). Pulse generated using SBC with triangular carrier wave.

The shoot through duty ratio (D_0), boost factor (B) and voltage gain (G) with triangular carrier wave are given by,

$$D_0 = 1 - M \tag{15}$$

$$B = \frac{1}{2M-1} \tag{16}$$

$$G = \frac{M}{2M-1} \tag{17}$$

where M is the modulation index.

b) SBC with sine carrier PWM [9]

In the conventional method of simple boost control, it is necessary to boost the shoot through duty ratio to achieve boosted output voltage which is possible with the low value of modulation index. But the decrement in modulation index leads to high voltage stress on the device. So it restricts the gain. The simple boost control with high frequency sinusoidal carrier wave helps to maximize the output voltage for a given modulation index. For the same modulation index the sinusoidal carrier PWM

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can give higher shoot through duty ratio compared to triangular carrier wave and gives high boost factor and hence high peak output voltage [9]. The reference sinusoidal voltage signals along with the sinusoidal carrier wave and two envelopes are shown in Figure-4a. The pulses produced using this method is shown in Figure-4b.

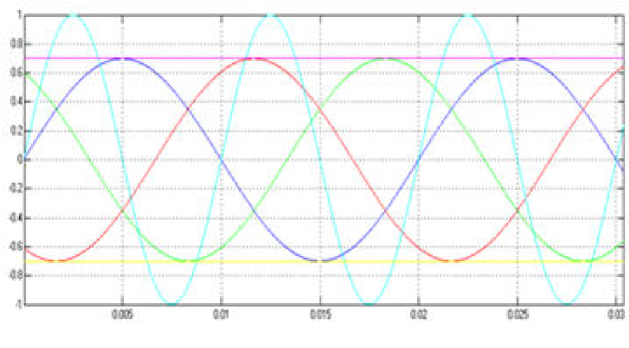

Fig 4(a) Illustration of SBC with sine carrier PWM

Figure-4(a). Illustration of SBC with sine carrier PWM.

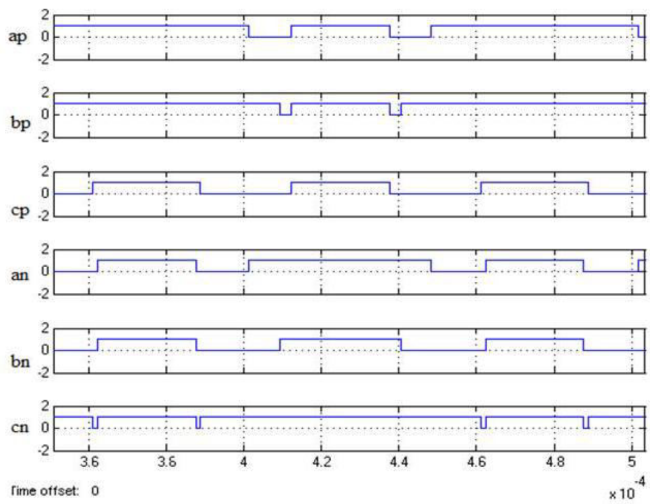

Figure-4(b). Pulse generated using SBC with sine carrier PWM.

The relations between shoot through duty ratio (d), boost factor (B) and voltage gain (G) with sine carrier wave are as follows [9],

$$d = 1 - \frac{2}{\pi}\sin^{-1} M \tag{18}$$

$$B = \frac{\pi}{4\sin^{-1} M - \pi} \tag{19}$$

$$G = \frac{\pi M}{4\sin^{-1} M - \pi} \tag{20}$$

c) Maximum boost control [10]

In this method, all the zero states are turned into shoot through state and hence the voltage stress is minimized. Voltage gain is improved. The circuit is in shoot through state when the triangular carrier wave is either higher than the maximum curve of the references (V_a, V_b and V_c) or lower than the minimum of the references. The shoot-through duty cycle varies each cycle. Maximum boost control method introduces a low frequency current ripple associated with the output frequency in the inductor current and the capacitor voltage. This will cause a higher requirement of the inductance and capacitance when the output frequency becomes low [10]. The illustration of maximum boost control is shown in Figure-5a and the pulses obtained are shown in Figure-5b.To increase the modulation index range, third harmonic injection is commonly used in a three-phase inverter system. Thus voltage gain is increased. The illustration of maximum boost control with third harmonic injection is shown in Figure-6a and pulses produced are shown in Figure-6b. In this control, the maximum modulation index $M = 2/\sqrt{3}$ can be achieved at 1/6 of third harmonic injection.

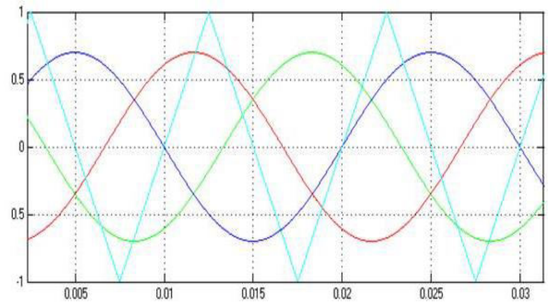

Figure-5(a). Maximum boost control.

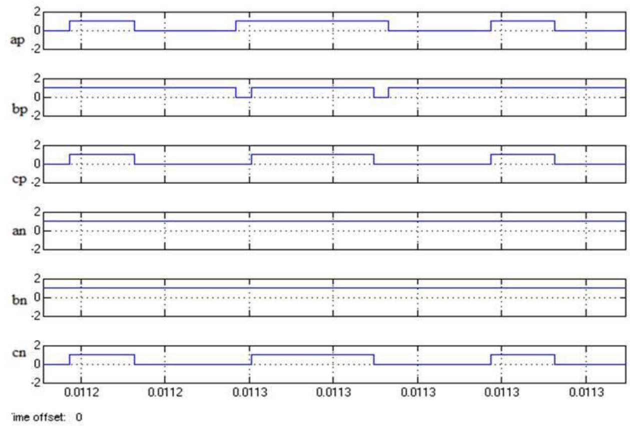

Figure-5(b). Pulse generated using maximum boost control.

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The relations between shoot through duty ratio (d) boost factor (B) and voltage gain (G) for maximum boost control are given as follows [10]:-

The shoot through state appears at the interval of $\left(\frac{\pi}{3}\right)$.Shoot through occurs at the interval $\left(\frac{\pi}{6},\frac{\pi}{2}\right)$ can be derived as,

$$\frac{T_0(\theta)}{T}=\frac{2-\left(MSin(\theta)-MSin(\theta-\frac{2\pi}{3})\right)}{2} \tag{21}$$

$$\frac{T_0(\theta)}{T}=\int_{\frac{\pi}{6}}^{\frac{\pi}{2}}\frac{2-\left(MSin(\theta)-MSin(\theta-\frac{2\pi}{3})\right)}{2}\,d\theta \tag{22}$$

$$=\frac{2\pi-3\sqrt{3}M}{2\pi} \tag{23}$$

Boost factor B is obtained as,

$$B=\frac{\pi}{3\sqrt{3}M-\pi} \tag{24}$$

$$G=\frac{\pi M}{3\sqrt{3}M-\pi} \tag{25}$$

Maximum modulation index for a given voltage gain G is,

$$M=\frac{\pi G}{3\sqrt{3}G-\pi} \tag{26}$$

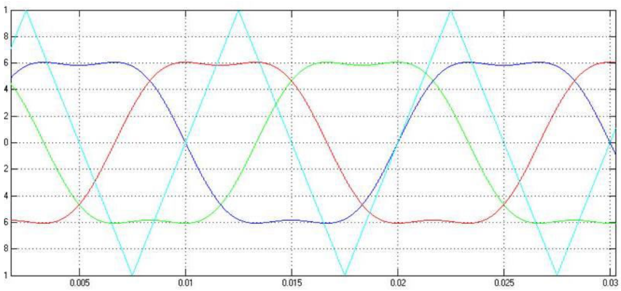

Figure-6(a). Illustration of maximum boost control with third harmonic injection.

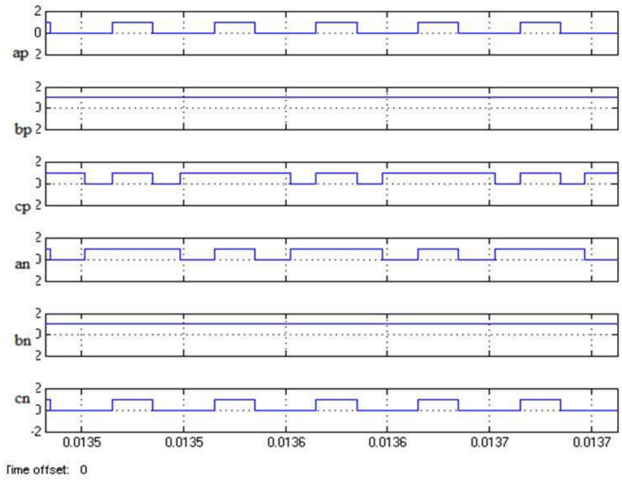

Figure-6(b). Pulse generated using maximum boost control with third injection harmonic.

The relations between shoot through duty ratio (d), boost factor (B) and voltage gain (G) for maximum boost control with third harmonic injection are given as follows:-

The shoot through state appears at the interval of every $\left(\frac{\pi}{3}\right)$ in this control also. The expression for the shoot through for the interval $\left(\frac{\pi}{6},\frac{\pi}{2}\right)$is given below [10],

$$\frac{T_0(\theta)}{T}=\frac{2-\left(MSin(\theta)+\frac{1}{6}MSin3\theta-MSin(\theta-\frac{2\pi}{3})+\frac{1}{6}MSin3\theta\right)}{2} \tag{27}$$

$$\frac{T_0(\theta)}{T}=\int_{\frac{\pi}{6}}^{\frac{\pi}{2}}\frac{2-\left(MSin(\theta)+\frac{1}{6}MSin3\theta-MSin(\theta-\frac{2\pi}{3})+\frac{1}{6}MSin3\theta\right)}{2}\,d\theta \tag{28}$$

$$=\frac{2\pi-3\sqrt{3}M}{2\pi} \tag{29}$$

Boost factor is given as,

$$B=\frac{\pi}{3\sqrt{3}M-\pi} \tag{30}$$

Also maximum modulation index can be obtained as $\frac{2}{\sqrt{3}}$.

d) Constant boost control [11]

It is necessary to keep the shoot through duty ratio constant to minimize the size and cost of the passive components. Also maximum voltage boost for any modulation index and reduced voltage stress can be obtained. Figure-7a shows the neat sketch of the constant boost control method to maintain the shoot-through duty ratio constant. The pulses produced using constant boost control is shown in Figure-7b. The maximum constant

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boost control can be implemented using third harmonic injection.

This method produces the boosted voltage and current with less harmonic content. The voltage gain can be varied from infinity to zero smoothly by increasing M from $\frac{1}{\sqrt{3}}$ *to* $\frac{2}{\sqrt{3}}$ with shoot through states and then decreasing *M* to zero without shoot-through states. The third and higher order harmonic component can be injected into the fundamental component to reduce the harmonic distortion. Maximum constant boost control achieves maximum boosted voltage while keeping the shoot through duty ratio constant [11-12]. The illustration of constant boost control with third harmonic injection is shown in Figure-8a and the pulses produced using the method is also shown in Figure-8b. The distance between the upper and negative envelops are constant and its value is $\sqrt{3}M$ .So the duty ratio is constant and is expressed as [11],

$$\frac{T_0(\theta)}{T} = \frac{2-\sqrt{3}M}{2} = 1-\frac{\sqrt{3}M}{2} \tag{31}$$

The voltage gain G= $\frac{M}{\sqrt{3}M-1}$ (32)

The voltage gain reaches infinity when M is decreased to $\frac{\sqrt{3}}{3}$.

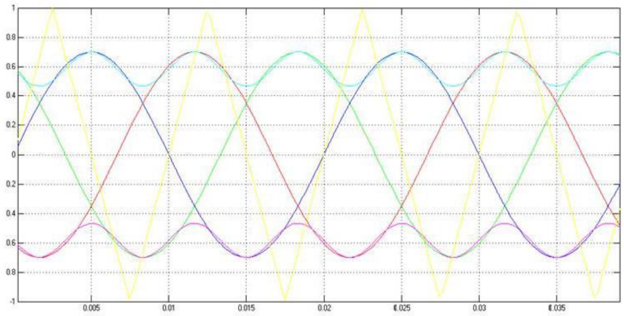

Figure-7(a). Illustration of constant boost control

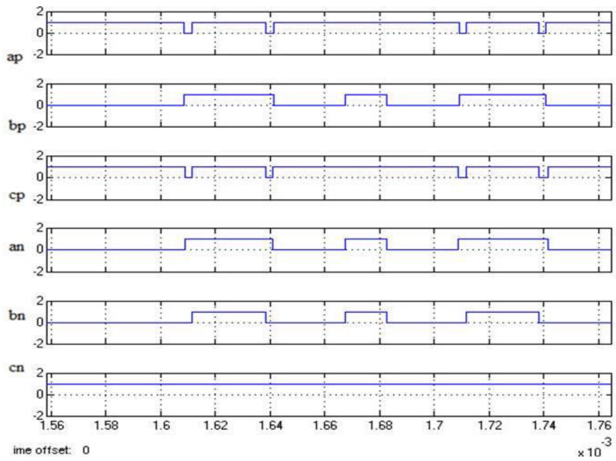

Figure-7(b). Pulse produced using constant boost control.

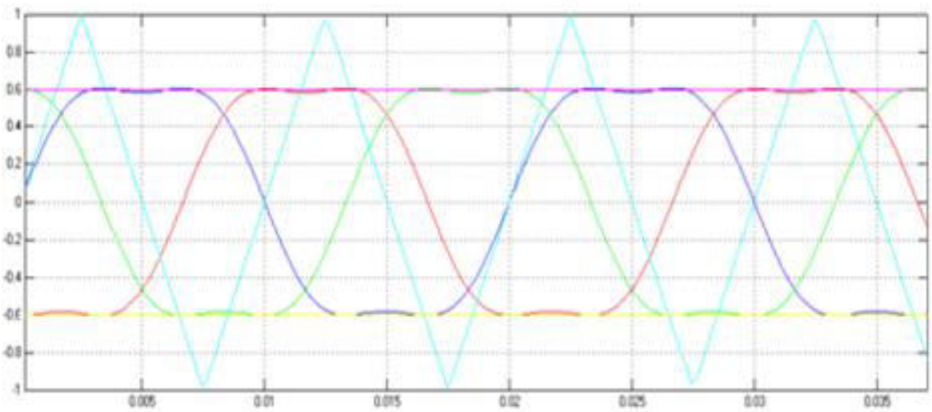

Figure-8(a). Illustration of maximum constant boost control.

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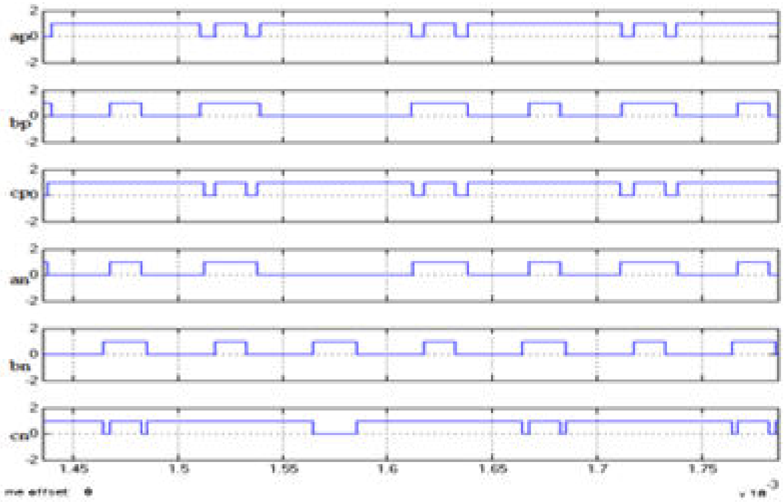

Figure-8(b). Pulses generated using maximum constant boost control.

Shoot through duty ratio is given as [11],

$$\frac{T_0(\theta)}{T} = \frac{2-\sqrt{3}M}{2} = 1 - \frac{\sqrt{3}M}{2} \tag{33}$$

This control is similar to maximum constant boost control method. The only difference is that voltage gain is varied from infinity to zero with the increment in M from $\frac{1}{\sqrt{3}} to \frac{2}{\sqrt{3}}$.

e) Traditional space vector PWM (SVPWM) control [13]

The classical SVM method is used in industrial application of pulse width modulated inverter because of its lower current harmonics and high modulation index. The modified SVPWM is used in ZSI. This modified SVPWM has an additional shoot through time T_0 for boosting the voltage of the inverter in addition to the time intervals T_1, T_2 and $T_{Z.}$ Shoot through states are evenly distributed to each phase with $T_0/6$ within zero voltage period. Zero voltage periods is minimized for producing shoot through interval and active states remain unchanged [13-18]. So shoot through period does not affect the PWM control of the inverter. The sketch map of the traditional SVPWM technique is shown in Figure-9.

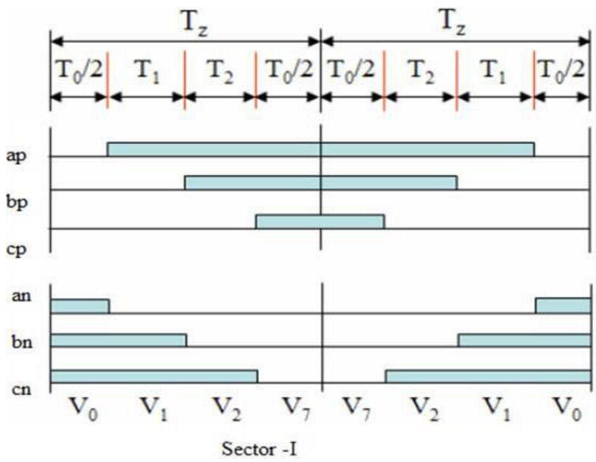

Figure-9. Switching state of Sector-I in traditional SVPWM control.

VI. RESULTS AND DISCUSSIONS

Simulations are carried out to verify all PWM control methods. The simulation parameters are given as:- input voltage =64V; Load: three phase star connected RL load of R=125Ω , L=1mH; the Z - source network: L1 = L2 =7.15 mH, C1 = C2 = 54.47μF; switching frequency = 10 KHz. The simulation results are obtained using the modulation index of M = 0.7 using different PWM control methods are given in Figure-10.

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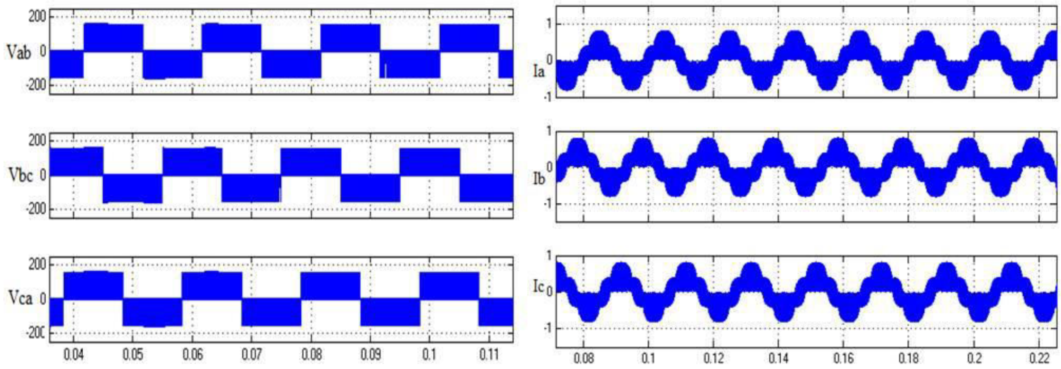

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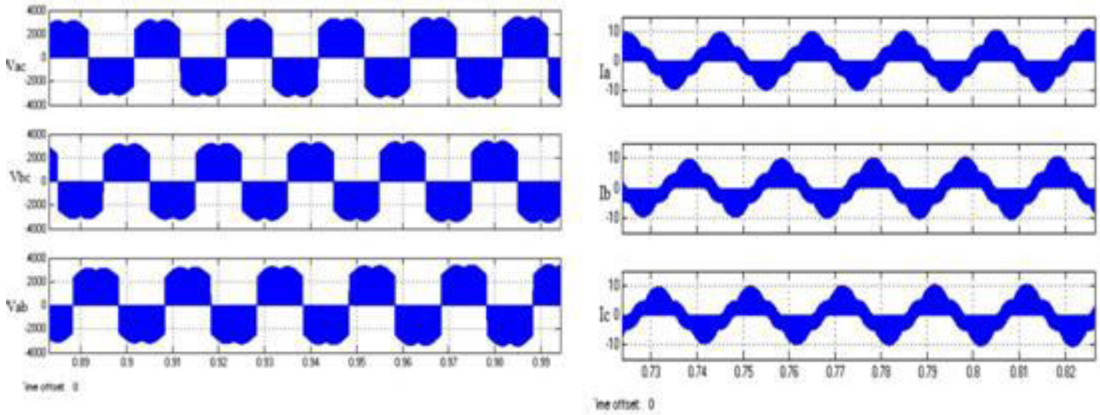

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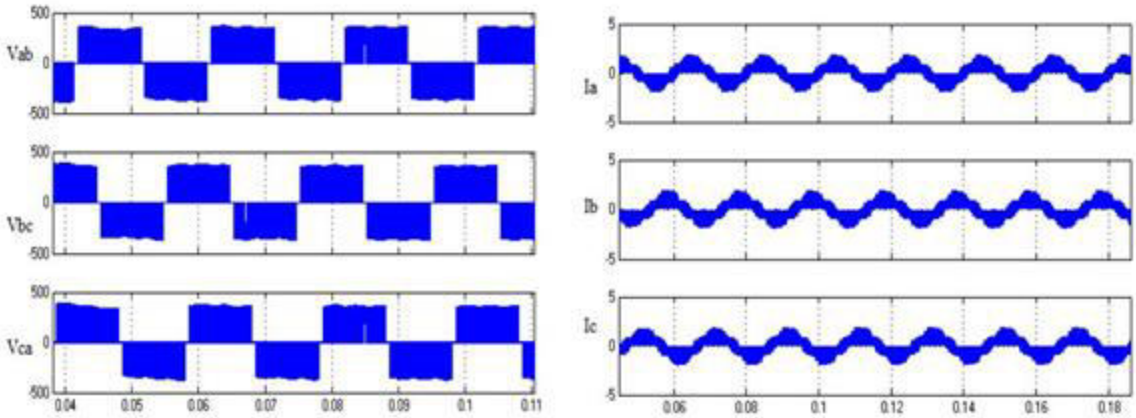

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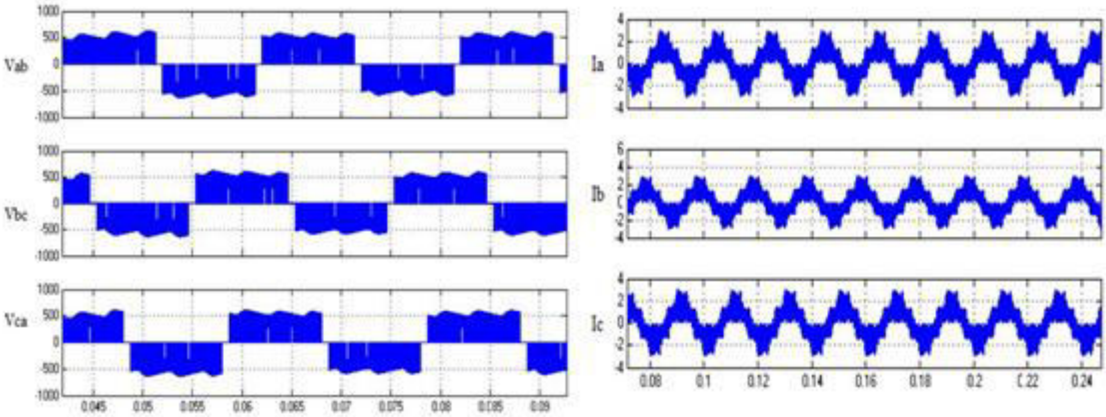

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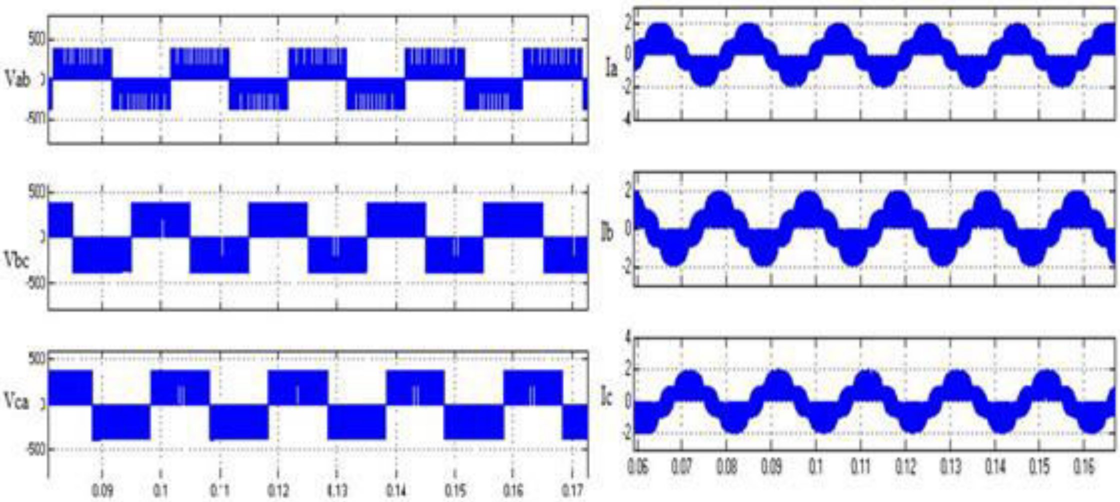

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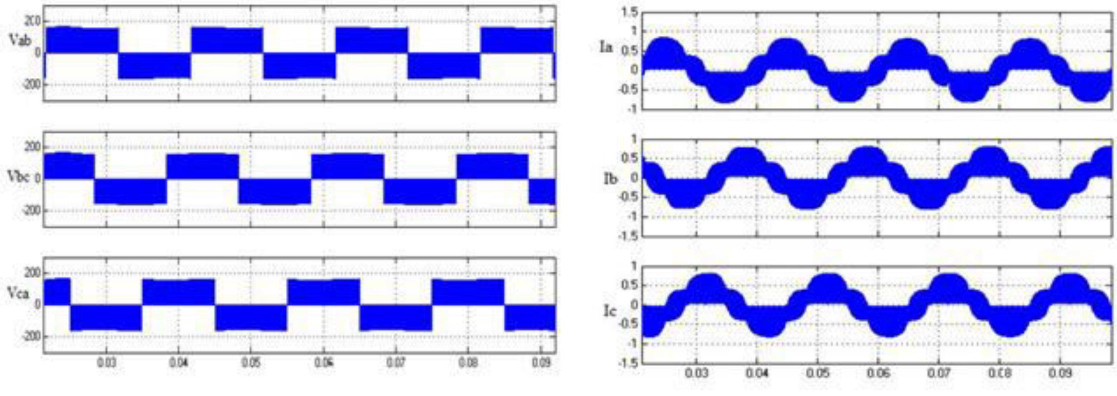

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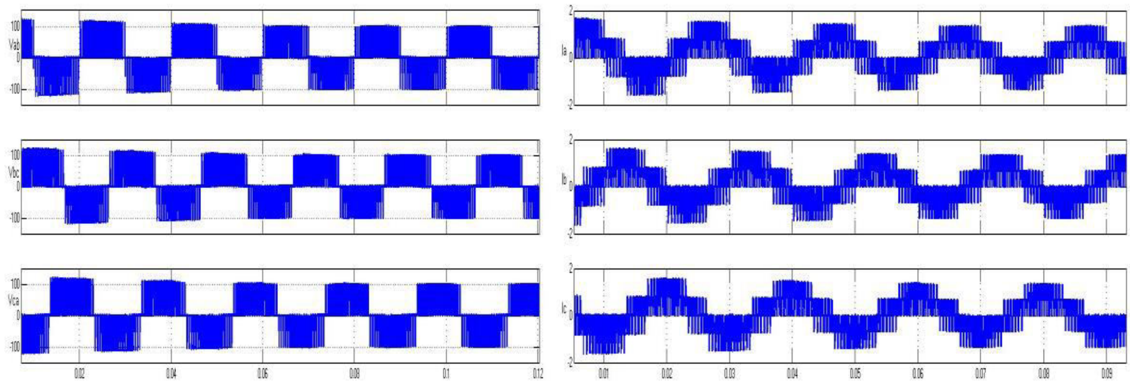

(g)

Figure-10. Simulation results of line to line voltages (Volts) and load currents (A) using different control methods with Modulation index (M) = 0.7

(a) SBC with triangular carrier wave
(b) SBC with sine carrier wave
(c) Maximum boost control
(d) Maximum boost control with third harmonic injection
(e) Constant boost control
(f) Constant boost control with third harmonic injection
(g) Traditional SVPWM control

VII. COMPARISON OF VARIOUS PWM CONTROL METHODS

The relation between voltage gain and modulation index has been plotted which is shown in Figure-11(a). Also the relation between voltage stress and the modulation index of various control techniques have been plotted and shown in Figure-11(b).

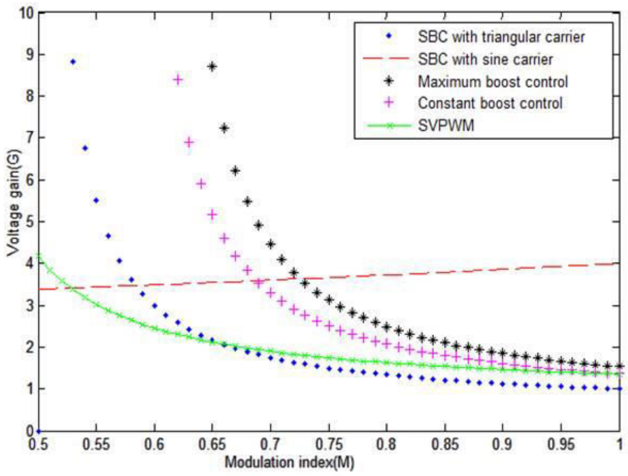

Figure-11(a). Modulation index vs. voltage gain.

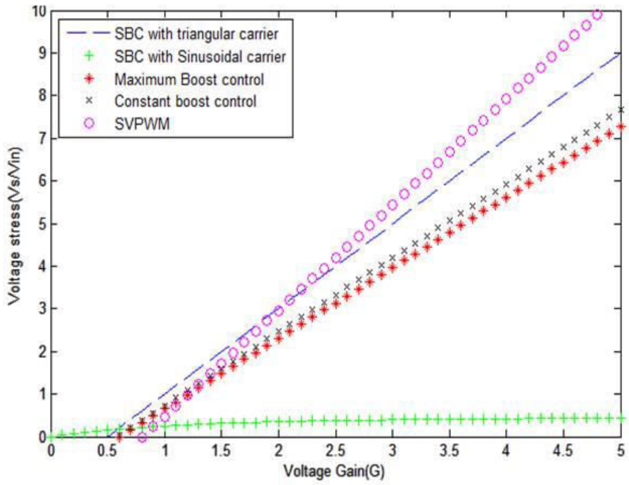

Figure-11(b). Voltage gain vs. (vs/vin).

Table-1 shows the comparison between shoot through duty ratio, boost factor, voltage gain, modulation index of various PWM control techniques [19].

Table-1. Comparison of various PWM control expressions.

PWM control method	SBC (with triangular carrier)	SBC (with sine carrier)	MBC	MBC with third harmonic injection	CBC	CBC with third harmonic injection	Traditional SVPWM control
Shoot through duty ratio (D_0)	1-M	$\frac{\pi - 2\sin^{-1}M}{2\pi}$	$\frac{2\pi - 3\sqrt{3}M}{2\pi}$	$\frac{2\pi - 3\sqrt{3}M}{2\pi}$	$\frac{2-\sqrt{3}M}{2}$	$\frac{2-\sqrt{3}M}{2}$	$\frac{3(2\pi - 3\sqrt{3}M)}{4(2\pi)}$
Gain (G)	$\frac{M}{2M-1}$	$\frac{\pi M}{\sin^{-1}M}$	$\frac{\pi M}{3\sqrt{3}M-\pi}$	$\frac{\pi M}{3\sqrt{3}M-\pi}$	$\frac{M}{\sqrt{3}M-1}$	$\frac{M}{\sqrt{3}M-1}$	$\frac{4\pi M}{9\sqrt{3}M-2\pi}$
Boost factor(B)	$\frac{1}{2M-1}$	$\frac{\pi}{\sin^{-1}M}$	$\frac{\pi}{3\sqrt{3}M-\pi}$	$\frac{\pi}{3\sqrt{3}M-\pi}$	$\frac{1}{\sqrt{3}M-1}$	$\frac{1}{\sqrt{3}M-1}$	$\frac{4\pi}{9\sqrt{3}M-2\pi}$
Modulation index(M)	1	1	1	$2/\sqrt{3}$	1	$2/\sqrt{3}$	1
Voltage stress (Vs)	$(2G-1)Vin$	$\frac{\sin^{-1}G}{\pi}Vin$	$\frac{3\sqrt{3}G-\pi}{\pi}Vin$	$\frac{3\sqrt{3}G-\pi}{\pi}Vin$	$(\sqrt{3}G-1)Vin$	$(\sqrt{3}G-1)Vin$	$\frac{9\sqrt{3}G-4\pi}{2\pi}Vin$

In conventional space vector modulation (SVM) method, the shoot-through current for each phase is double the inductor current which increases the current stress on the switch [20]. The shoot-through is equally distributed on the three legs of the inverter bridge when simple boost control (SBC), maximum boost control (MBC), constant boost control (CBC) methods are used for producing boosted output voltage as shown in, Figure-10a and Figire-10b. Also the maximum boost control is suitable for applications where a fixed or relatively high output frequency is required. Constant boost control method is used for reducing the passive components, mainly in variable-speed-drive applications.

VIII. CONCLUSIONS

Simulation of all open loop modified sinusoidal PWM control methods of Z-source inverter is carried out with same input voltage and load conditions. The boost factor, voltage gain, duty ratio, and voltage stress across the switches for all the methods are analyzed. It shows that maximum boost control can give more boosted output voltage. Also better performance can be obtained if modulation index (M) and shoot-through duty ratio (D_0) are fixed to a high value. Various control methods are useful in promoting the applications of ZSIs.

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