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Proposed Method for Shoot-Through in Three Phase ZSI and Comparison of Different Control Techniques

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Article Info	ABSTRACT
	This paper presented the new methodology for different control techniques applied to three phase Z-source inverter for minimisation of switching losses. The procedure for proposed control techniques and its effects on the performance of operation of three phase Z-source inverter are analyzed. The graphs for voltage gain and voltage stress are drawn for different control methods. The flow-chart for the symmetrical and unsymmetrical control techniques for creating pulse signals for switches of three phase inverter are shown. All the methods are studied and compared with each other. The Total harmonic distortion (THD) of output voltage of both the control methods has been analyzed using FFT analysis. The experiments done and the results shown for capacitor voltage, load current and load line voltage for simple boost and constant boost control techniques are presented using MATLAB/ Simulink.

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1.   INTRODUCTION

The conventional voltage-source inverter (VSI) is used in industries to control the speed of AC motor drive, which consist of diode rectifier at front end, DC link capacitor and inverter bridge[1]. Similarly, in order to transfer energy from PV array into utility grids, the voltage-source inverter is used to convert the DC voltage into AC voltage. VSI is a buck converter that can only produce an AC voltage limited by DC link voltage, which is roughly equal to 1.35 times the input line voltage, if three phase diode bridge rectifier is used at front end [2], [3]. Inrush and harmonic current from the diode bridge rectifier can decreases the efficiency and produces pulsating torque which creates the noise and vibration of ASD system. Low power factor is another issue of the traditional ASD system. Performance and reliability can be achieved by overcoming the three important factors like miss-gating from EMI can cause shoot-through that leads to destruction of the inverter, the dead time that is needed to avoid shoot-through, which increases the complexity of control technique, an output LC filter is needed for providing a sinusoidal voltage compared with the current source inverter, which causes additional power loss and control complexity [4]. There are eight states in one cycle of operation of voltage source inverter. Out of which six states are called active states in which the DC link voltage is impressed across the load and two zero states where the load terminals are shorted through either the lower and upper three device respectively. The voltage across the load is zero in two zero state conditions. Amplitude modulation control the width of zero states and thus the voltage across the load is

regulated but remain well below the DC-link voltage. Therefore, VSI has only one control variable i.e.modulation index which is used for buck the voltage across the load. The Z-source inverter employs an X-shape network before the traditional voltage-source inverter bridge. During shoot-through period the capacitor voltage is boosted up by receiving the energy from inductor, while producing no voltage to load. It should be emphasized that both the shoot-through zero state and the two traditional zero states short the load terminals and produce zero voltage across the load, thus preserving the same PWM properties and voltage waveform to the load. The only difference is that the shoot-through zero state boost the capacitor voltage, where as the traditional zero states do not have boosting capability. For the same output voltage the total harmonic distortion is less in Z-source inverter compared to traditional voltage-source inverter because of active-state voltage across the load is the capacitor output voltage [5], [6]. There are four ways of introducing shoot through in a Z-source inverter, out of which one method is very common in traditional method, where all the switches of all three legs are made ON at a time.but in this method the main disadvantage is the swiching losses occurs during the switching action of switches. This paper presents a new technique of shoot through which will no doubt minimize the switching losses fulfilling the shoot through purposes in a Z-source inverter during null state period. The Z-source inverter circuit analysis, criteria for choosing the value of passive parameters, proposed control techniques for providing shoot-through. Simulation results are included to prove the concept. Figure 1 shows the main circuit configuration of the Z-source inverter with 3-phase load. Similar to that of the traditional voltage source inverter.

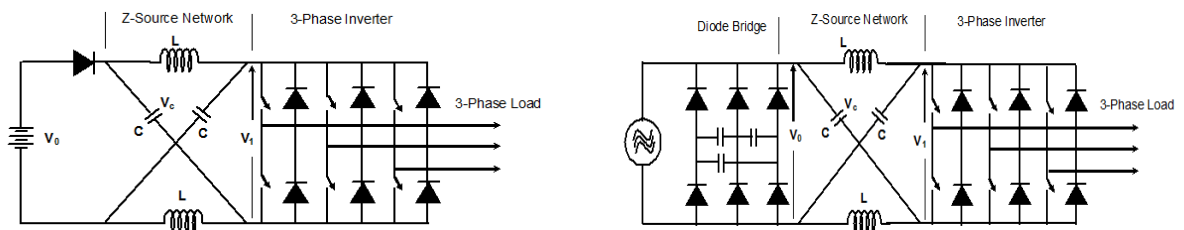## 2. CIRCUIT CONFIGURATION, OPERATING PRINCIPLES AND MODES OF OPERATION

Figure 1. (a, b) Z-source inverter with 3- phase load.

The Z-source inverter circuit consists of three parts: a three-phase, single-phase diode bridge rectifier or battery depending upon the availability of input system, DC-link circuit , and an inverter bridge. Small input capacitors are connected to the diode bridge rectifier if diode bridge rectifier is used instead of battery. For battery as input, a diode is connected before dc-link to oppose the flow of energy towards source during shoot-through period. The dc link circuit of Z-source inverter is different from traditional voltage-source inverter and it consist of symmetrical X shape network consist of series inductance and shunt capacitance ($L_1=L_2=L$, $C1=C_2=C$). For a diode bridge rectifier as input Fig1(b), at any instant of time, only two phases that have the largest potential difference may conduct, therefore as viewed from Z-source network, the diode bridge can be modeled as a dc source in series with two diode, acts just like as battery with diode. The operating control technique of switching of the inverter is such a way that the inverter operates in three modes: active mode, traditional zero-state mode and shoot-through zero state mode. The modes of operation are explained assuming the operation of Z-source inverter is only three dynamic states.

2.1. Active-state -1

The inverter bridge is operating in one of the six traditional active vectors (100,010,110,001,101,011), thus acting the output as a current source viewed from the Z-source circuit. In this mode the power is taken from the source and feed to the load. The continuous flow of input current reduces the harmonic current. This mode of operation is shown in Figure 2(a).

2.2. Zero-state-1

The inverter bridge is operating in one of the two traditional zero vectors (111,000) and shorting through either the upper or lower three devices, thus acting as a open circuit viewed from the Z-source circuit. In this mode, the input is connected to the impedance network and input current is the inductor current, which contribute to the line current's harmonic reduction. This state may be completely or partially

compensated by shoot-through state depending on control technique applied to inverter switches. Completely compensated mode is named as 3-mode operation whereas partially compensated mode is called as 2-mode operation in this paper. This mode of operation is shown in Figure 2(b).

2.3. Shoot-through- state-1

The inverter bridge is operating in one of the seven shoot-through states. During this mode the input is disconnected and load is shorted through Z-source network. Seven shoot-through are achieved by turning all switches or five switches or 4 switches at a time. The control technique is such that the shoot-through state is inserted during the period of zero-state without affecting the period of active state. It can be seen that the shoot-through interval is only a fraction of switching cycle; therefore it needs a small capacitor to suppress voltage. During this period the energy stored in the inductor is transferred to the capacitor and hence the capacitor voltage is boosted up. Depending on how much a boost voltage is needed, the shoot-through interval is determined. This mode of operation is shown in Figure 2(c).
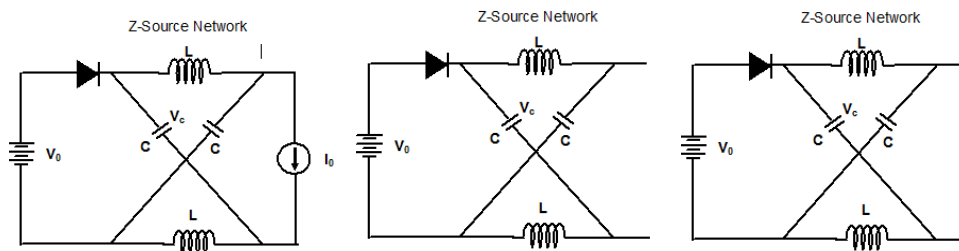

Figure 2. (a, b, c) Different modes of operation of Z-source inverter.

3.   DIFFERENT CONTROL TECHNIQUES

Figure 3(a, b) shows   the traditional PWM switching sequence based on the triangular carrier signals compared with the 3 sinusoidal signals with a phase difference of 120^0 for $M_a = 0.5$. In every switching cycle, the zero states (000 or 111) are created along with active states. In Z-source inverter, without affecting the active states, the shoot-through states is allocated in zero-state intervals evenly to boost the voltage. If the shoot-through state is completely allocated in zero-state interval then the operation is called two -mode operation, otherwise the operation is called three-mode operation.
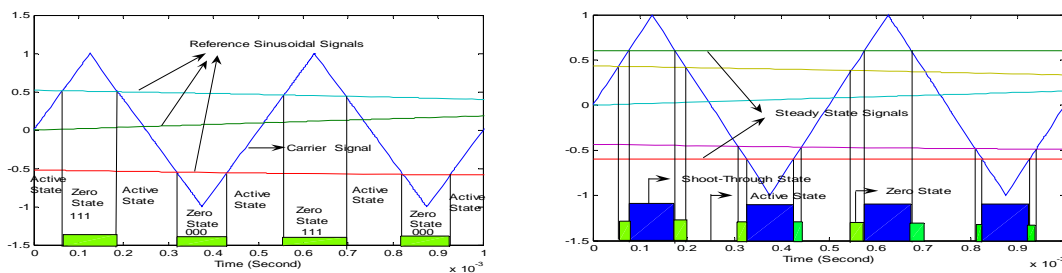

Figure 3. (a, b) Switching Techniques of traditional VSI and ZSI using simple boost control.

3.1.   Simple boost control

In this method, the shoot-through time per switching cycle is kept constant, thus having a constant boost factor [6]. From the figure of VSI switching cycle it is confirmed that the zero state is produced when all the sinusoidal waveforms are less or greater than carrier signal. Therefore, to provide shoot –through in zero state the other two steady signals, whose amplitudes are equal to amplitude of sinusoidal waveform and one is negative magnitude of other are compared with triangular signal. The proposed procedures can be used to produce different shoot-through combinations. Different shoot-through combinations can be obtained by including the comparative output of steady-state signals and carrier signal. Symmetrical switching occurs when the above comparative outputs are used for all the legs of the inverter. In this case, the shoot –through period is produced by turning on all the switches. By doing this, the switching frequencies of all the switches are doubled as compared to VSI inverter which increases the switching losses. Unsymmetrical switching

occurs when the comparative outputs are used in any one leg or any two legs. In this case the switching frequencies of switches have different values. For example, if the shoot-through is created in a-phase then the switching frequency of a -phase switch is twice the other switches of b and c phases. As a result, the switching losses can be minimized by providing the shoot-through in one phase only. However , at the same time the current stress in each switches during shoot-through is three times(4 switches on) or two times (5 switches on) when compared with symmetrical switching. Another advantage of this control method is that the dc inductor current and capacitor voltage have no ripples that are associated with the output frequency, because of shoot through period is constant over one switching cycle. Figure 3(b) shows how the shoot-through state is included in zero-state interval without affecting the active state intervals.[7]-[11]. The average DC-link voltage across the inverter bridge is same as the capacitor voltage can be represented as :

$$V_1 = V_0 = \frac{T_1}{T_1 - T_0} V_0 \tag{1}$$

The peak DC-link voltage across the inverter bridge is represented as

$$\hat{V}_1 = \frac{T}{T_1 - T_0} V_0 \tag{2}$$

Where,

$$B = \frac{T}{T_1 - T_0} = \frac{1}{1 - \frac{2T_0}{T}} \geq 1 \tag{3}$$

Since $T_1 + T_0 = T$ is the boost factor resulting from the shoot- through zero state. T_0 is the shoot-through zero state interval, T is the switching period and T_1 is the combination of active-state and zero-state intervals. $\hat{V}_1$ is the input voltage appeared before Z-source network. V_c is the capacitor voltage which is same as the average dc-link voltage V_0 appeared after Z-source network. On the other side, the output peak phase voltage from the inverter can be expressed as :

$$\hat{V}_{ao} = M_a \frac{\hat{V}_1}{2} = M_a B \frac{V_0}{2} \tag{4}$$

Where, M_a is the modulation index.The peak DC-link voltage across the inverter bridge is represented as voltage stress V_{stress} of the inverter.

$$V_{stress} = B V_0 \tag{5}$$

Let $\frac{T_0}{T} = D_0$ (shoot-through duty ratio) and $M_a = \frac{T_1}{T}$ (assuming no zero-state interval),then

$M_a = 1 - D_0$ (When the magnitude of steady state signal is same as the amplitude of sinu-soid signal)

$$B = \frac{1}{1 - 2D_0} \tag{6}$$

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

The ratio of the voltage stress to the equivalent to the equivalent dc voltage denoted as voltage stress for same output voltage ($V_{so} = B V_0 / G V_0$) for the simple boost control is as:

$$V_{so} = 2 - \frac{1}{G} \tag{8}$$

It can be concluded from the above equations that :
- The modulation index and shoot-through duty ratio are interdependence with each other if magnitude of steady-state signal is equal to the amplitude of sinusoidal signal and the ranges of M_a and B are lying in between 0.5 to 1 and 0.5 to 0 respectively.
- This method is used to boost the output voltage, theoretically to infinity but practically it is limited to 3 to 4 times due to parasitic elements of impedance network and switches.

To make the modulation index and shoot-through duty ratio independent with each other and to control by two degrees of freedoms M_a and B for boost and buck the output voltage, the steady-state signal is to be controlled and it should be greater than the peak of sinusoidal signal.

3.2. Maximum constant boost control

In order to reduce the voltage stress and increase the modulation index from 1 to $2/\sqrt{3}$, the Maximum constant boost control technique is used. A sketch map of Maximum constant boost control method is shown in Fig.4(b). The flow charts of symmetrical and unsymmetrical control technique for maximum constant boost control are same as the simple boost control, except the reference signals.

$$V = V_m \sin wt + 1/6 \sin 3wt \qquad (9)$$
$$V = V_m \sin(wt - 120°) + 1/6 \sin 3wt \qquad (10)$$
$$V = V_m \sin(wt + 120°) + 1/6 \sin 3wt \qquad (11)$$

For phase A, B and C respectively.

$$\frac{T_0}{T} = \frac{2 - \sqrt{3}M_a}{2} \qquad (12)$$

$$B = \frac{1}{1 - 2D_0} = \frac{1}{\sqrt{3}M_a - 1} \qquad (13)$$

$$G = M_a B = \frac{M_a}{\sqrt{3}M_a - 1} \qquad (14)$$

Theoretically, the gain is infinite when $M_a = 0.577$. Therefore the ranges of M_a and B are lying in between 0.577 to $2/\sqrt{3}$ and 0.423 to 0 respectively. The ratio of the voltage stress to the equivalent to the equivalent dc voltage denoted as voltage stress for same output voltage ($V_{so} = BV_0/GV_0$) for the maximum constant boost control is as:

$$V_{so} = \sqrt{3} - \frac{1}{G} \qquad (15)$$

3.3. Maximum boost control method

In order to completely eliminate the zero state and thus maximize the voltage boost and minimize the voltage stress for the same output voltage the maximum boost control method is used. The shoot through state is achieved when the triangular carrier signal is either greater than the maximum curve of three sinusoidal references or smaller than the minimum of the references. Figure 4 (a, b, c) show the modulation technique to provide shoot-through and driver signals for the six switches of simple boost control, maximum constant boost control and maximum boost control. With taking average of varying shoot through times from Figure 4(b) the boost factor, voltage gain and voltage stress are given by following equations.

$$B = \frac{1}{1 - 2D_0} = \frac{\pi}{3\sqrt{3}M_a - \pi} \qquad (16)$$

$$G = M_a B = \frac{M_a \pi}{3\sqrt{3}M_a - \pi} \qquad (17)$$

In this control, the ranges of M_a and B are lying in between 0.604 to 1 and 0.4 to 0 respectively. The ratio of the voltage stress to the equivalent to the equivalent dc voltage denoted as voltage stress for same output voltage ($V_{so} = BV_0/GV_0$) for the maximum constant boost control is as:

$$V_{so} = \frac{3\sqrt{3}}{\pi} - \frac{1}{G} \qquad (18)$$

The range of M_a and the output frequency are also deciding factors for selection of control technique.[12], [13]. The waveform of different control techniques and the graphs for Voltage gain and Voltage stress comparison of different control methods are shown in figure 4(a, b, c) and figure 5(a, b).
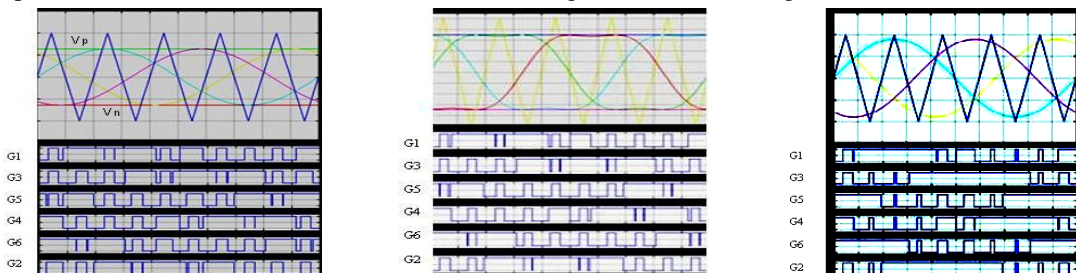
Figure 4. (a, b, c) Waveform of simple boost maximum constant boost and maximum boost respectively.
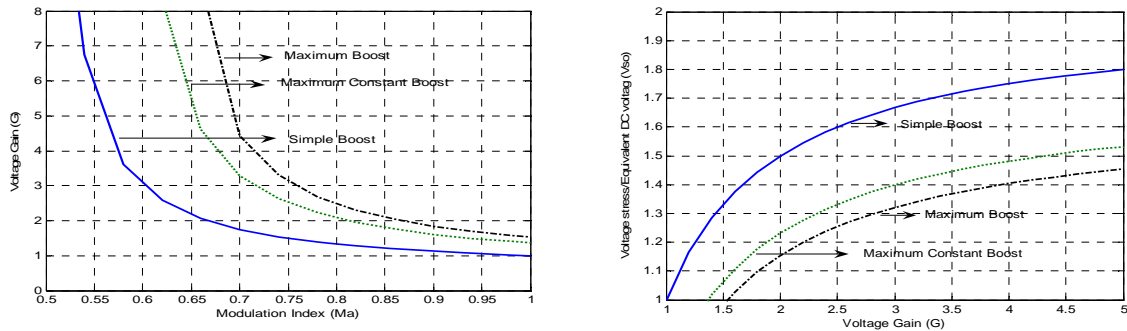

Figure 5 (a, b) Voltage gain and Voltage stress comparison of different control methods respectively.

The flow charts of symmetrical and unsymmetrical control technique for creating pulse signals of switches of inverter of simple boost control are shown in Figure 6 (a,b,c) and Figure 7 (a,b,c) respectively. The flow charts are designed for generating pulses for switches of ZSI. Similar switching phenomena can be implemented to other control techniques.
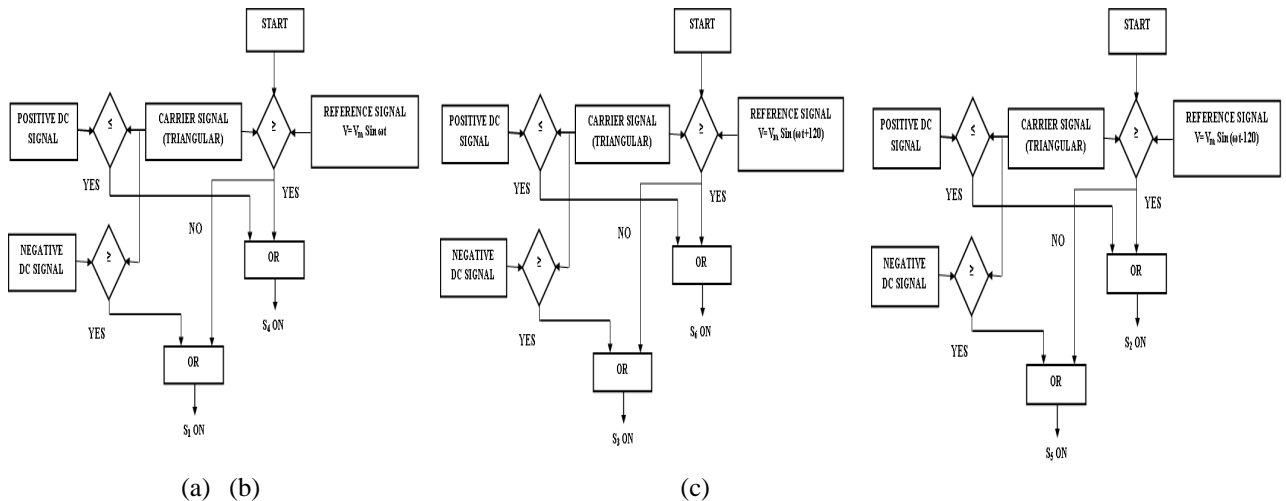

(a)   (b)   (c)

Figure 6. (a, b,c) Flow charts of simple boost symmetrical control technique.

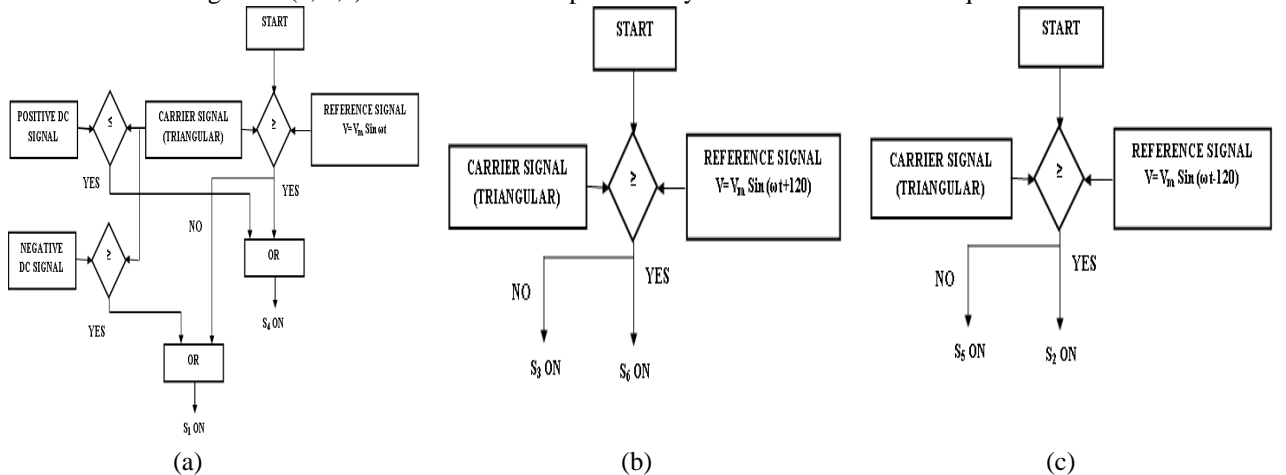(a)   (b)   (c)

Figure 7. (a, b,c) Flow charts of simple boost unsymmetrical control technique.

4. OPERATION OF INVERTER IN 3 MODES KEEPING AMPLITUDE MODULATION CONSTANT

Different modes operation is achieved by simple boost control and maximum constant boost control. In the above control methods, shoot through is provided by using pair of steady state values (straight lines) unequal to the peak maximum and minimum of the sinusoidal reference signals and non-sinusoidal signals (sinusoidal

signals with injected third harmonic signal) for simple boost and maximum constant boost control respectively. The advantage of the above methods is the output voltage is controlled by independent control of amplitude modulation and shoot-through duty ratio (two degrees of control). The unsymmetrical control technique and without affecting the active state is the advantageous control technique is the proposed control technique and can be carried out by using pair of steady state values (straight lines) greater than peak maximum and minimum of the sinusoidal reference signals and non-sinusoidal signals for simple boost and maximum constant boost control respectively and used for comparing it to one leg signal for providing different width of shoot-through by turning on one switch of that leg. Based on highest voltage boost requirement, the amplitude modulation is chosen and makes to be constant. The voltage boost is controlled by changing the magnitude of straight line and it must be greater or equal to amplitude modulation.

5.   SIMULATION RESULTS

To verify and compare different control methods, Matlab simulations were performed having following parameters.$L_1=L_2=0.5mH$,$C_1=C_2=2mF$,$V_0=100V$ (dc), Switching frequency = 2 KHz, 3-phase load: R/phase = 50 ohm,   L/phase = 2 mH. The simulation results of simple boost and maximum constant boost are shown in Figure 7(a,b,c) and Figure 8(a,b,c) respectively. The amplitude modulation is kept constant, 0.5 for simple boost and 0.5774 for maximum constant boost. The shoot–through duty ratio of both control techniques keeps at 0.6,so that the amplitude modulation and shoot-through duty ratio are independent with each other. We observe from figures, that the capacitor voltage and peak value of dc link inverter voltage of simple boost control method are same as produced by maximum constant boost control method. Further, it can be observed that there is no overshoot of capacitor voltage for both proposed techniques (shoot through duty ratio is greater or equal than amplitude modulation. It can be seen that the fundamental output line voltage (rms) of inverter is about 228V of simple boost and 260V of maximum constant boost through FFT analysis of output voltage for the same dc link inverter voltage. The above analysis indicates that the voltage stress across the inverter switches is higher of simple boost control technique than the maximum boost control technique. However, in maximum constant boost control method, the total harmonic distortion (THD) is 3.31% of fundamental, which is higher than simple boost control whose THD is about 1.36% of fundamental. In maximum constant boost control, the 3rd and 5th harmonic components of output voltage are about 3.22% and 0.27%, whereas in simple boost control method the above values are .18% and 0.9% of fundamental .This is because of the third harmonic component is injected in reference signal in maximum constant boost control method for generation of driver signals of switches.
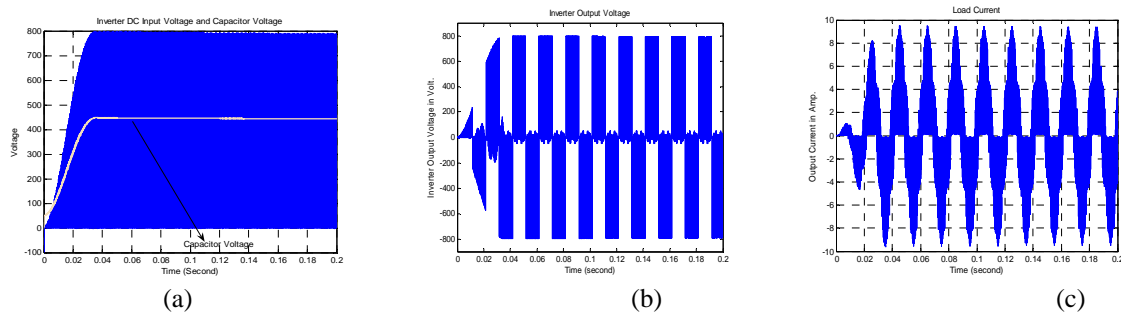

| (a) | (b) | (c) |

Fig.7(a, b, c) Simulated results of capacitor voltage load current and load line voltage of simple boost control technique.
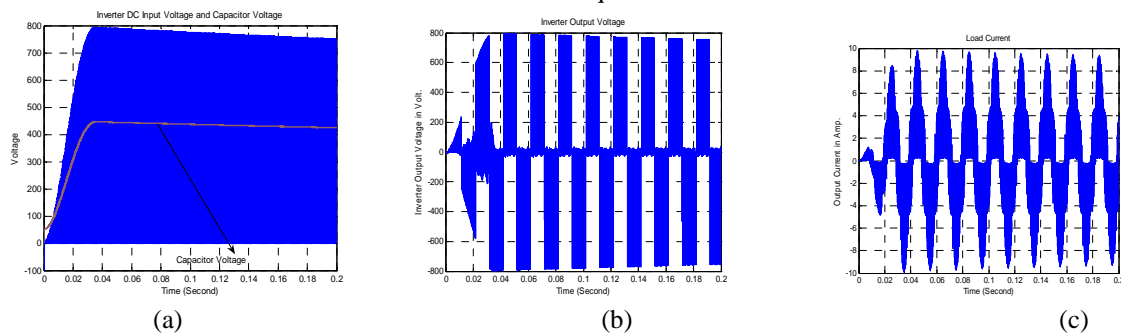

| (a) | (b) | (c) |

Fig.8(a, b, c) Simulated results of capacitor voltage load current and load line voltage of maximum constant boost control technique.

6.   CONCLUSION

Three control methods for providing shoot-through in 3-phase Z-source inverter has been analyzed and compared in this paper. The boost factor, Voltage gain, Overshoot of capacitor voltage, Voltage stress across the switches and THD of output voltage have been analyzed. Simulation of Z-source 3-phase inverter under simple boost and maximum constant using straight lines for providing shoot-through) have been presented, showing overshoot in capacitor voltage would not be occurred if the value of straight lines is greater than the peak value of sinusoidal for simple boost and peak value of non-sinusoidal (combination of fundamental and third harmonic sinusoid) signal.

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