



Sine Carrier for Fundamental Fortification in Three Phase Z-Source PWM Inverters

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Abstract

This paper deals with a novel natural sampled pulse width modulation strategy for three phase Z-source inverter through carrier modification. The proposed sine carrier method, which uses the conventional sinusoidal reference signal and a sine carrier, has a better harmonic spectrum and a higher fundamental component compared to the conventional triangular carrier based PWM. The sine carrier PWM enhances the fundamental output voltage while keeping the total harmonic distortion lower without involving changes in device switching loss. The detailed comparison of harmonic content and fundamental component of the sine carrier PWM output with the results obtained for the conventional PWM is also presented. Microcontroller is chosen for the hardware implementation of the switching strategy, mainly due to its high computation speed which can ensure the accuracy of the instants that gating signals are generated.

Keywords: Pulse width modulation, Sine carrier, Triangular carrier, Total harmonic distortion, Z-source inverter

1. Introduction

In a traditional voltage-source inverter, the two switches of the same phase leg can never be gated on at the same time because doing so would cause a short circuit(shoot through) to occur, which would destroy the inverter. In addition, the maximum output voltage obtainable can never exceed the dc bus voltage. An LC filter is also needed for providing a sinusoidal voltage, which causes additional power loss and complexity. These limitations can be overcome by the new Z-source inverter, shown in Figure.1. which uses an impedance network (Z network) to replace the traditional dc link. (F.Z. Peng, 2003)

The Z-source inverter advantageously utilizes the shoot through states to boost the dc-bus voltage by gating on both the upper and lower switches of a phase leg. Therefore, the Z-source inverter can buck and boost voltage to a desired output voltage that is greater than the available dc bus voltage. In addition, the reliability of the inverter is highly improved because shoot-through can no longer destroy the circuit. Thus it provides a low cost, reliable, and highly efficient single stage structure for buck and boost power conversion.

In the traditional PWM technique of the voltage source inverter, there are eight permissible switching states: six active and two zero states. During the two zero states, the upper three or the lower three switches are turned on simultaneously, thus shorting the output terminals of the inverter and producing zero voltage to the load. During one of the six active states, the dc voltage is impressed across the load, positively or negatively. In addition to the eight traditional switching states, the Z-source inverter has several shoot-through zero states, during which both the upper and lower switches of one or multiple same phase legs are turned on. It is obvious that during a shoot-through zero state, the output terminals of the inverter are shorted and the output voltage to the load is zero. Therefore, the shoot through states has the same effect (i.e., zero voltage) to the load as the traditional zero states; however, these shoot through states can boost the dc

voltage. The active states have to be kept unchanged to maintain the output voltage waveform, and the traditional zero states can be replaced partially or entirely by the shoot through zero states depending on how much voltage boost is needed.

All the traditional pulse width modulation (PWM) schemes can be used to control the Z-source inverter and their theoretical input-output relationships still hold. Several modified PWM control method for the Z-source inverter based on traditional control methods were presented in the literature. (Miaosen Shen, 2004; P.C.Loh et al, 2005). In the simple boost control method two straight lines are used to control the shoot through states. (F.Z.Peng, 2003; F.Z.Peng et al, 2005). This method has drawbacks of high voltage stress across devices. But the maximum boost control technique can achieve minimum voltage stress across devices and maximum boosted output voltage. However, it has the drawback of low frequency ripple associated with output frequency.

2. Proposed sine carrier PWM

The Z-source inverter intentionally utilizes the shoot-through zero states to boost dc voltage and produce an output voltage greater than the original dc voltage. But the shoot-through zero states do not affect the PWM control of the inverter, because it equivalently produces the same zero voltage to the load terminal. The available shoot-through period is limited by the zero-state period that is determined by the modulation index.

The voltage gain of the Z-source inverter can be expressed as (N.Mohan et al, 1995)

$$\frac{v_o}{V_{dc}/2} = M_a B \quad (1)$$

where v_o is the output peak phase voltage, V_{dc} is the input dc voltage, M_a is the modulation index, and B is the boost factor.

B is determined by

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

where D_o is the shoot through duty ratio.

In the conventional simple boost control method, a triangular carrier was used to control the shoot-through duty ratio. In this case, the shoot-through time per switching cycle is constant, which means the boost factor is constant. In this conventional triangular carrier PWM the shoot through duty ratio is given as

$$D_o = 1 - M_a \quad (3)$$

In this conventional simple boost control method, to achieve the high output voltage, it is required to increase the shoot through duty ratio, which can only be achieved with the reduction of modulation index. But small modulation index results in greater voltage stress on the device, hence it restricts the obtainable gain because of the limitation of device voltage rating.

The proposed control strategy uses the conventional sinusoidal reference while the carrier wave is a modified one. The control scheme uses a high frequency sine carrier that helps to maximize the output voltage for a given modulation index.

For the proposed PWM, the shoot through duty ratio is determined by

$$D_o = \frac{(\pi - 2 \sin^{-1} M_a)}{2\pi} \quad (4)$$

The boost factor B and the voltage gain can be calculated:

$$B = \frac{\pi}{\sin^{-1} M_a} \quad (5)$$

$$\frac{v_o}{V_{dc}/2} = M_a B = \frac{\pi M_a}{\sin^{-1} M_a} \quad (6)$$

For the same modulation index, the sine carrier PWM gives higher shoot through duty ratio as compared to that of triangular carrier PWM. In the conventional simple boost control method, the triangular carrier waveform is replaced by a sine waveform to generate gating pulses shown in Figure.2. It is worth while to note that in both the PWM methods

the number of pulses generated will be the same and hence constant switching loss is guaranteed. (S.Jeevananthan et al, 2007)

Figure.3. gives the variation of shoot through duty ratio for different modulation index with constant carrier frequency. The sine carrier gives higher shoot through duty ratio without any pulse dropping at given modulation index while makes the dependency a little non linear.

3. Simulation results

To show the effectiveness of the proposed modulator, simulation was performed for different modulation index values. The simulation was conducted with the three phase Z-source inverter with the following parameters: Z-source network: $L_1 = L_2 = 3.09$ mH, $C_1 = C_2 = 54.4$ μ F, switching frequency is 10 kHz. The purpose of the system is to compare the performance of the Z-source inverter under the conventional triangular carrier PWM and the proposed sine carrier PWM. Figure.4. shows the simulated output waveforms and Figure.5. gives the harmonic spectrum of the output line voltage when triangular carrier PWM is used. The similar simulation results when sinusoidal carrier PWM used are shown in Figure.6. and Figure.7. The modulation index used in both the simulations is $M_a = 0.88$. The shoot-through zero state is populated evenly among the three phase legs, achieving an equivalent switching frequency of 60kHz viewed from the Z-network. Therefore, the required dc inductor L is minimized. From the above analysis, we have the following theoretical calculations:

For triangular carrier PWM

$$B = 1.316$$

$$v_o = 141.8\text{V (line to line rms)}$$

For sinusoidal carrier PWM

$$B = 2.92$$

$$v_o = 314.7\text{V (line to line rms)}$$

For the same modulation index the sine carrier PWM gives high boost factor and hence high peak output voltage. Also it gives higher fundamental output voltage. To increase the fundamental amplitude in the triangular PWM technique the only way is increasing M_a beyond 1.0, which is called as an overmodulation. Overmodulation causes the output voltage to contain many lower order harmonics and also it makes the fundamental component – modulation index non-linear. From the simulation analysis the proposed PWM gives less magnitude of lower order harmonics and hence lower values of total harmonic distortion (THD) in the output voltage. The THD and lower order harmonics magnitude are tabulated in Table.1. for the two PWM methods with a modulation index of 0.88.

4. Hardware implementation

The laboratory model for Z-source inverter as shown in Figure.8.was constructed. The same parameters as the simulation were used. The microcontroller PIC 18F4550 was used for firing pulse generation. The pulses obtained from the microcontroller were amplified using the driver chip IR2125. The gating pulse waveforms and the output line voltage waveform are given in Figure.9 and Figure.10.

5. Conclusion

The paper presents a novel sine carrier PWM scheme for controlling the output of the three phase Z-source inverter with improved fundamental component value at the given modulation index. Also this new method gives lower THD in the output voltage compared to the conventional triangular carrier PWM. In addition, this new method does not require any mode change and causes exactly same number of switching per cycle. Analytical, simulation, and experimental results have been presented. The Z-source inverter can buck-boost voltage, minimizes component count, increase efficiency and reduce cost.

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Table 1. Comparison of THD, fundamental and lower order harmonics

Method	THD (%)	Fundamental Voltage V1 (V)	Third Harmonic V3 (%V1)	Fifth Harmonic V5 (%V1)	Seventh Harmonic V7 (%V1)	Ninth Harmonic V9 (%V1)	Eleventh Harmonic V11 (%V1)
Triangular Carrier PWM	4.14	199.6	0.08	2.89	2.86	0.02	0.38
Sine Carrier PWMS	2.53	300.1	0.05	1.96	1.45	0.0	0.18

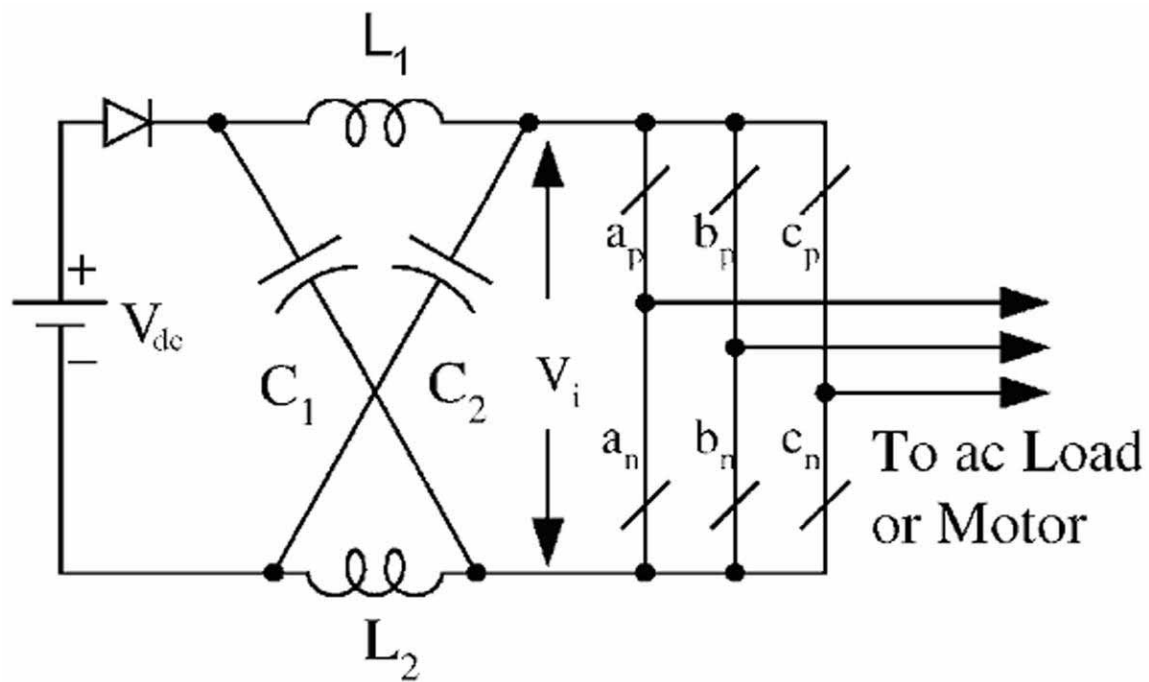


Figure 1. Z-source inverter

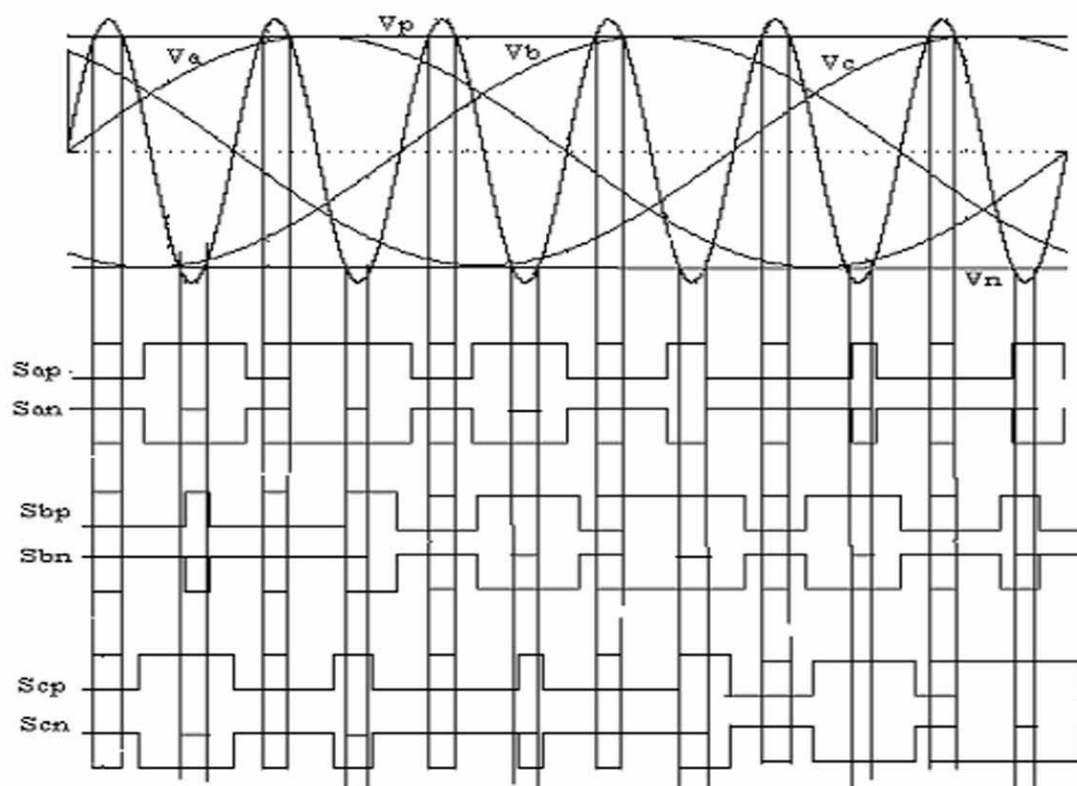


Figure 2. Proposed sine carrier PWM

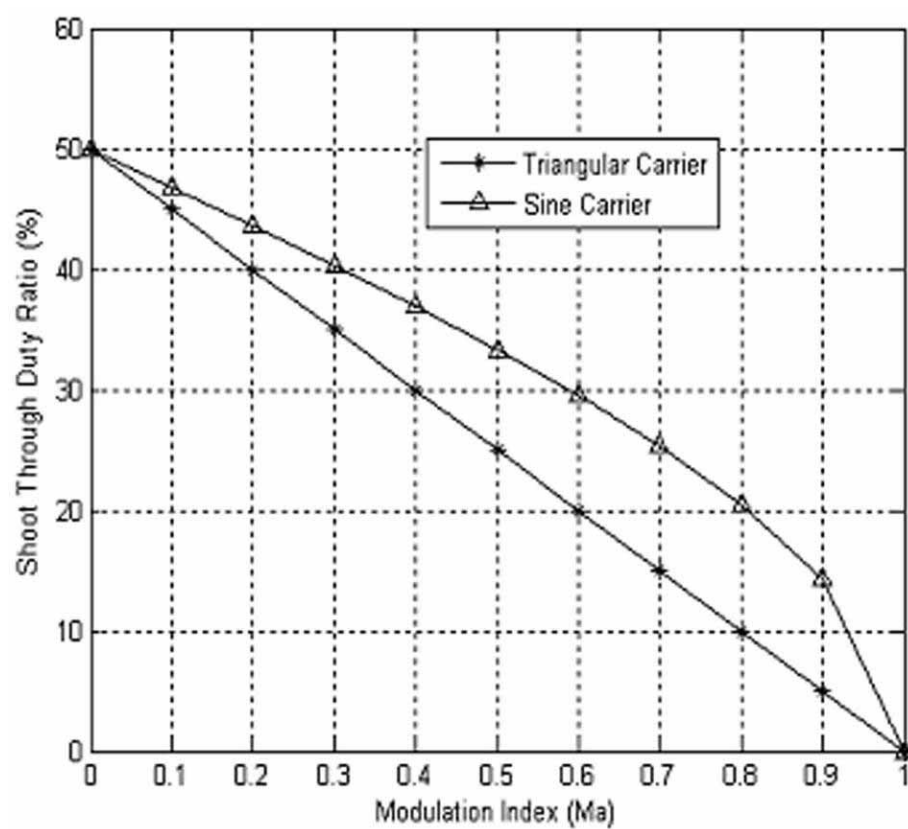


Figure 3. Modulation index vs shoot through duty ratio.

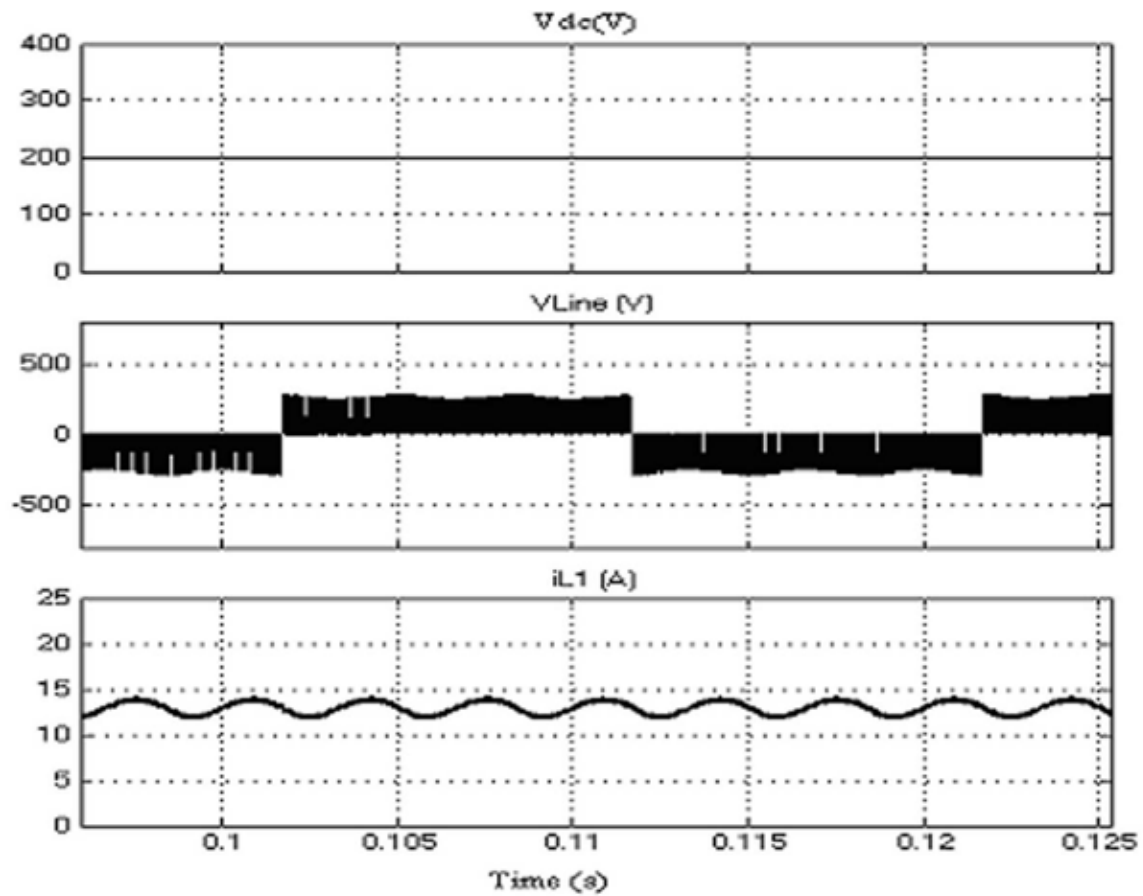


Figure 4. Simulation results with $M_a = 0.88$ using Triangular carrier PWM.

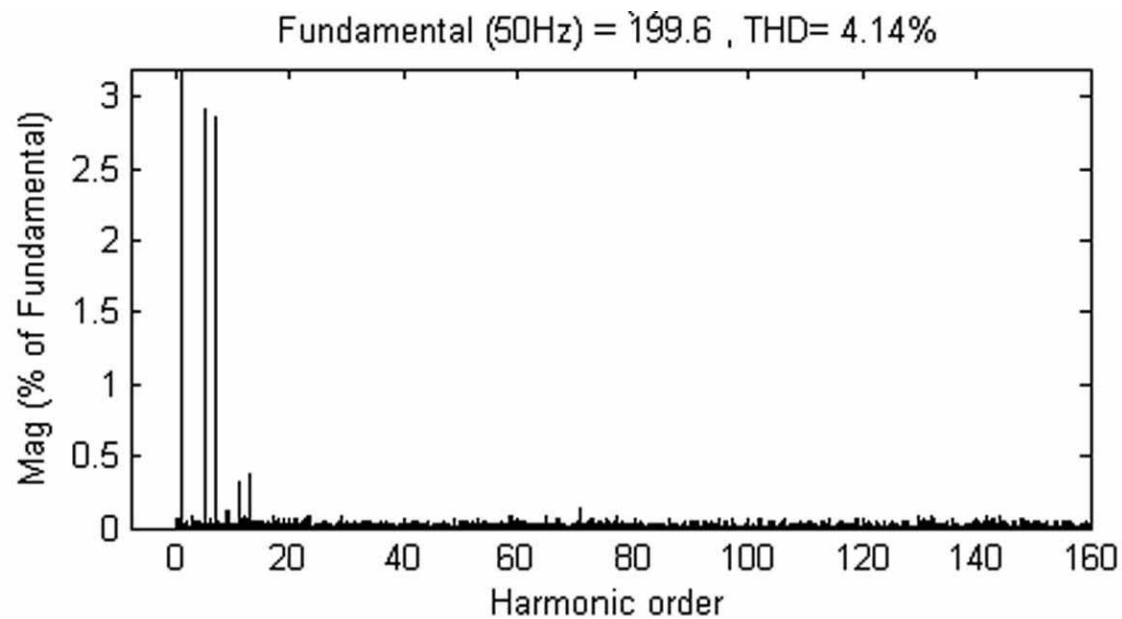


Figure 5. Simulated Harmonic Spectra of Z-source inverter with $M_a = 0.88$ using Triangular carrier PWM

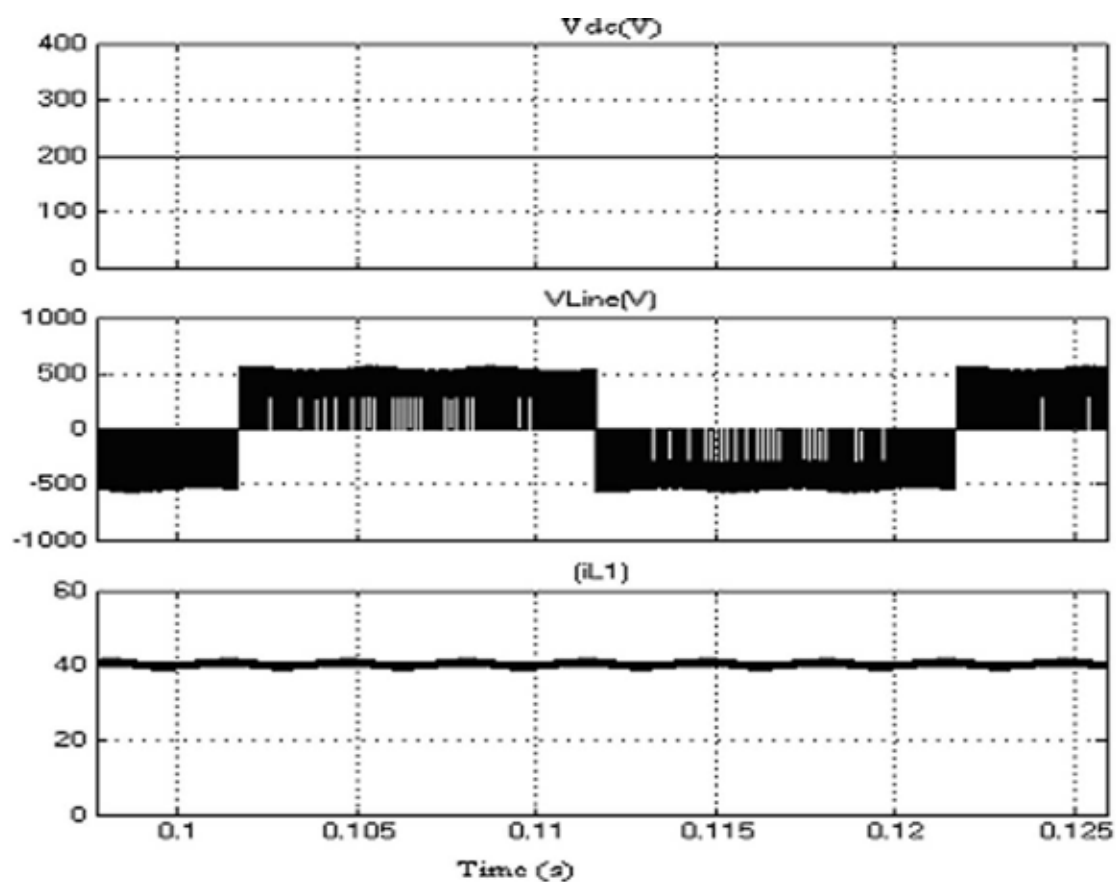


Figure 6. Simulation results with $M_a = 0.88$ using Sine carrier PWM

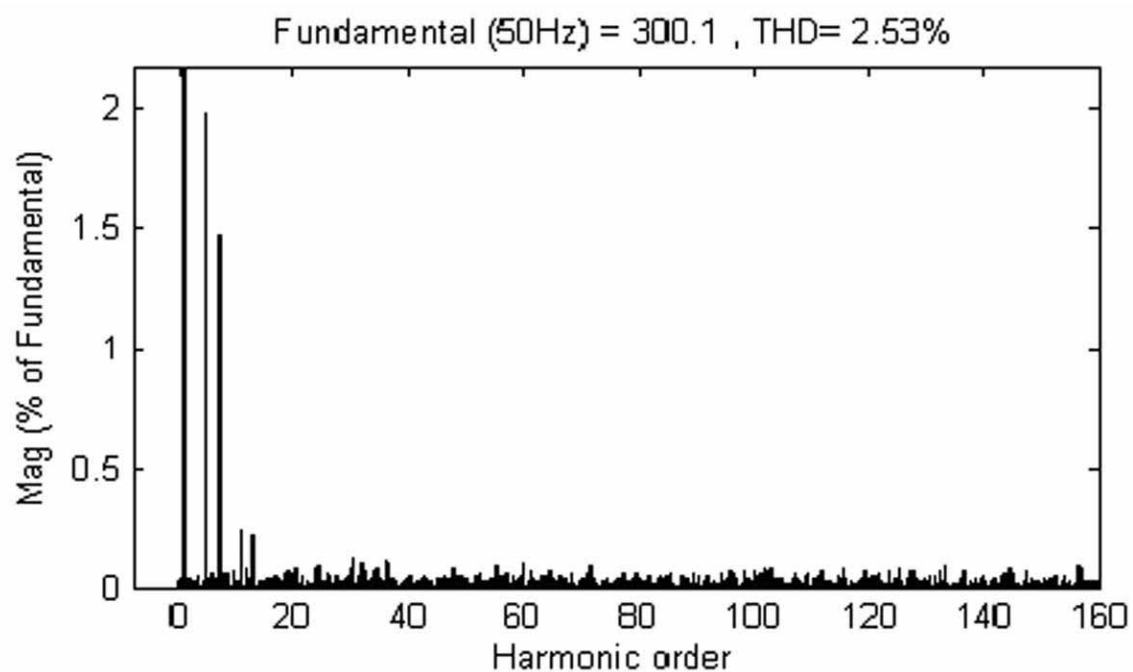


Figure 7. Simulated Harmonic Spectra of Z-source inverter with $M_a = 0.88$ using Sine carrier PWM

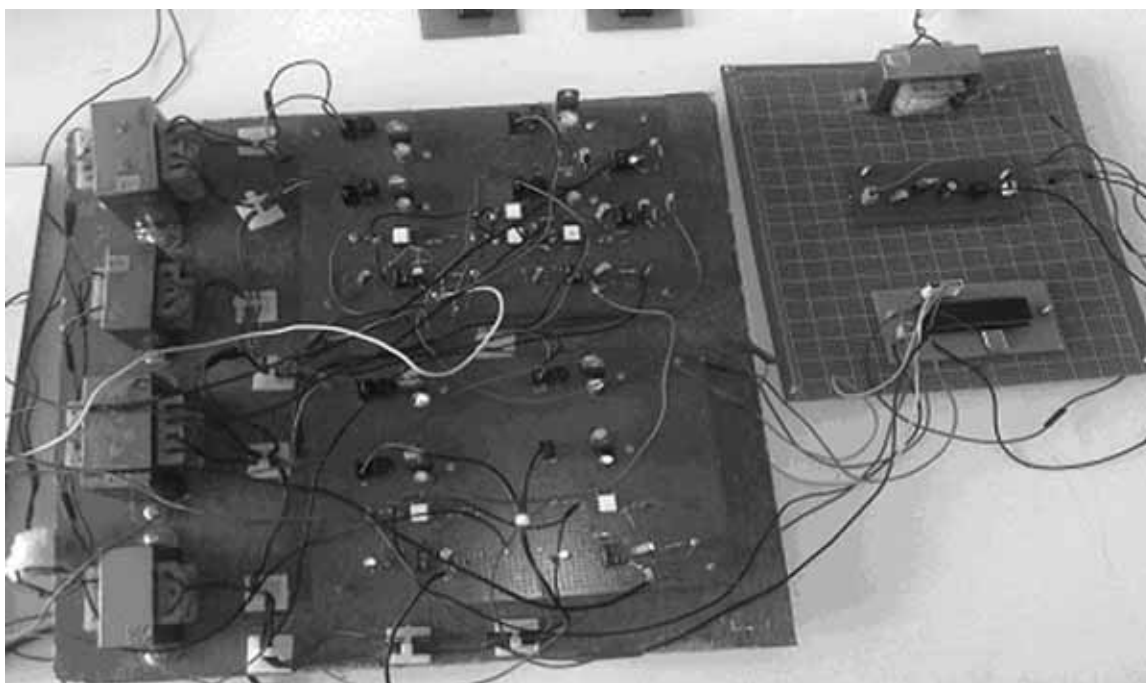


Figure 8. Hardware circuit

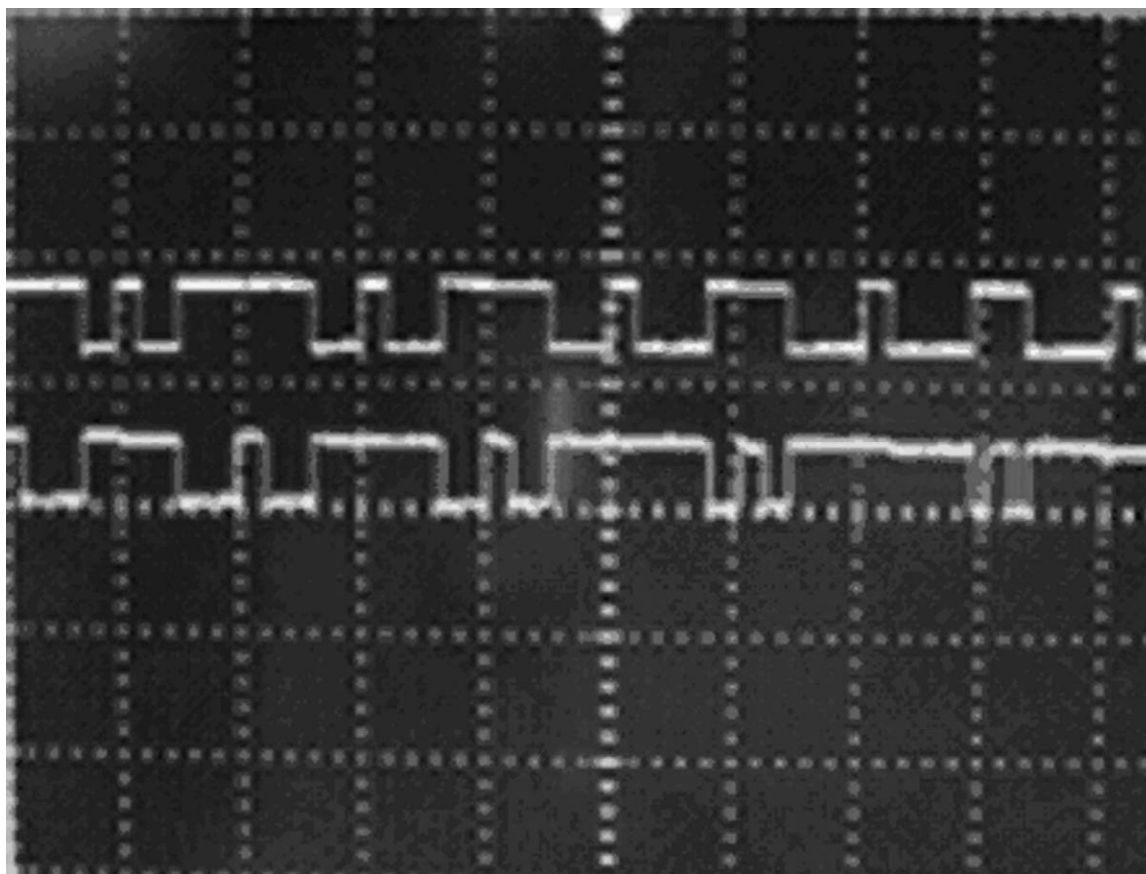


Figure 9. Firing pulses for switches S_{ap} and S_{an}

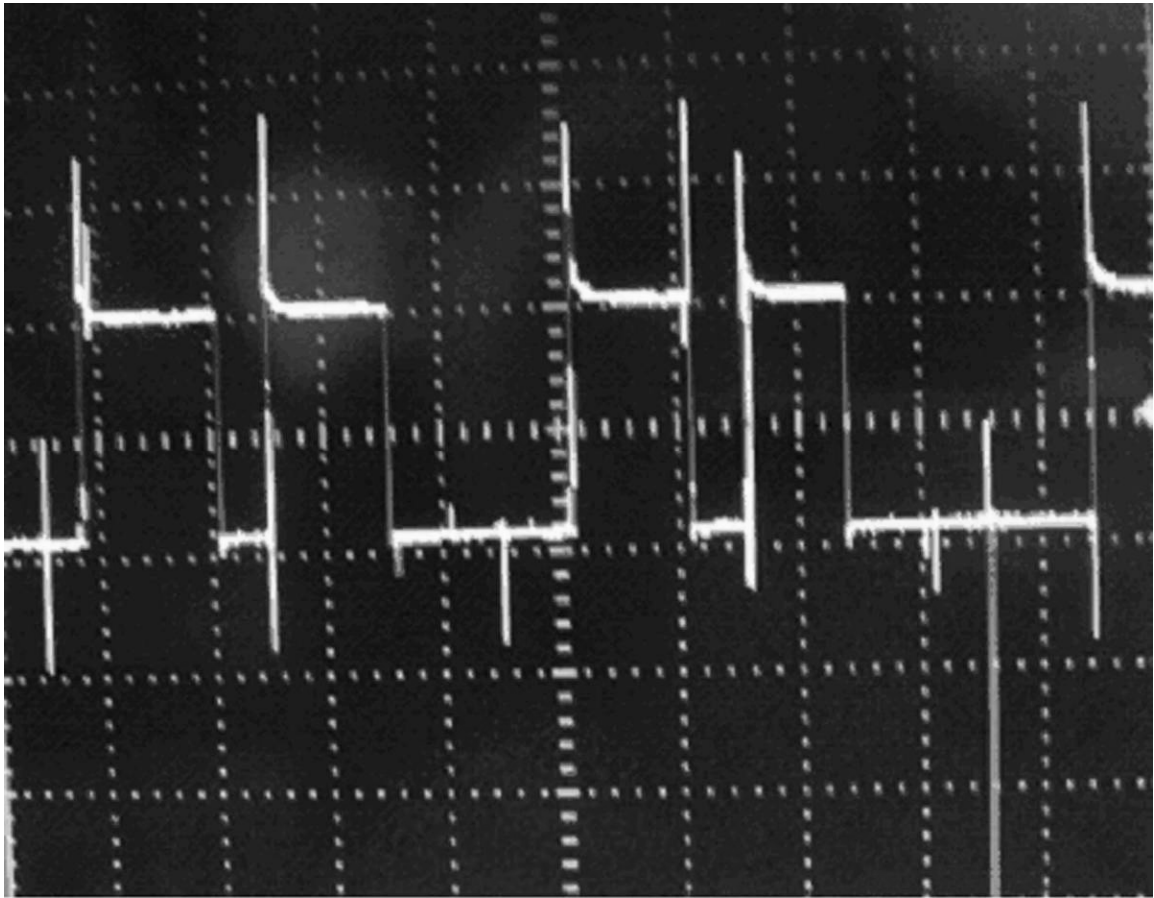


Figure 10. Output line voltage