Comparison of PWM Techniques for the Performance Improvement of Z-Source Inverter

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Abstract—*This paper presents the three PWM techniques for the performance improvement of Z-Source Inverter (ZSI). The ZSI overcomes the drawbacks of VSI and CSI. By increasing or decreasing the shoot through time period, the output voltage could be increased. Hence, in this new topology step up transformer or dc-dc booster to boost the voltage is not required. The operating modes of three-phase ZSI are discussed in this chapter. The mathematical equations for boost factor, shoot through duty ratio, voltage gain and voltage stress are mathematically obtained and validated by simulation results. The two Pulse Width Modulation (PWM) techniques Simple Boost (SB) PWM and Maximum Boost (MB) PWM are implemented for the ZSI and the results are compared.*

Keywords—*ZSI, PWM, Boost factor, Voltage gain*

I. INTRODUCTION

The Z-Source Inverter (ZSI) employs a unique impedance network (LC network) to link the power source and inverter main circuit to provide both voltage buck and boost properties which cannot be obtained in traditional voltage source inverter (VSI) and current source inverter (CSI) where a capacitor and inductor are used respectively [1 and 2]. The Z-Source inverter overcomes the conceptual and theoretical barriers and limitations of the traditional voltage source inverter (VSI) and current source inverter (CSI) [3 and 4]. The new Z-Source inverter reduces line harmonics, and extends output voltage range. The circuit diagram of three-phase ZSI is shown in Fig 1. The Z-source inverter has X shape, unique impedance network (LC network) to link the DC source and inverter main circuit to provide both voltage buck and boost properties [1]. The Z-source network consists of two identical inductors L1, L2 (L1=L2) and two identical capacitors C1, C2 (C1=C2) [5]. This impedance network is used to buck or boost the voltage depending upon the value of boost factor [6]. This boost factor can be varied by varying the shoot through time [7].

II. SWITCHING STATES OF Z-SOURCE INVERTER

The ZSI is a buck-boost inverter in which the obtainable output ac voltage can be any value between zero and infinity [8]. This unique feature of the ZSI is obtained by the additional switching state called shoot through state. The conventional VSI has eight permissible switching states such as six active states when the DC voltage is absorbed across the load and two zero states when the load terminals are short-circuited through the upper or lower switches in the inverter. However, the ZSI has seven additional switching states called shoot through zero state [9]. This shoot through zero state could be obtained by turning on the upper and lower switches in any one phase leg, two phase legs or all the three-phase legs. During the shoot through state, load terminals are short circuited through the upper and lower switches of the same leg.

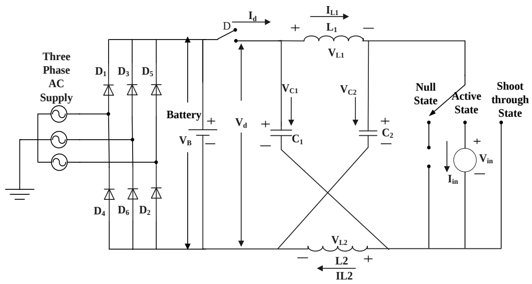

Fig 1. Circuit diagram of three-phase ZSI

III. EQUIVALENT CIRCUIT OF ZSI

The three operating modes of three-phase ZSI are,

- Mode 1: Null state or Zero state
- Mode 2: Shoot-through state
- Mode 3: Non shoot-through state

A. Mode 1 - Null state or Zero state

The three-phase ZSI is in null state or zero state, when the three upper switches or the three lower switches in the inverter are tuned on. This state is present in the traditional VSI also. During this state the inverter bridge is equivalent to open circuit when it is viewed from the DC link.

B. Mode 2 – Shoot through state

The shoot through state of the ZSI is the switching state at which the switches in the same phase leg of the three-phase inverter are turned ON. During this operating state the H- bridge inverter is equivalent to a short circuit and the diode D is reverse biased [1]. The load is disconnected from the battery input during the shoot through state because of higher voltages in inductors. The ZSI is working in shoot through state during time interval Tshoot, where Tshoot is a shoot through time period in seconds.

The switching time period (Ts) of the ZSI is the sum of shoot through time period (Tshoot) and non shoot through time period (Tactive). The Shoot through time period (Tshoot) is defined as the duration at which the switches in the same phase leg are turned on at the same time. The non shoot through time period or active time period (Tactive) is the duration at which the ZSI is operating in any one of the six active states.

The switching time period Ts is given by,

$$T_s = T_{shoot} + T_{active} \tag{1}$$

During the shoot through state the L1 and C1 are connected in parallel similarly L2 and C2 are connected in parallel which is shown in Figure 3.7. The Z-source inverter utilizes this shoot through state to boost the DC link voltage to the inverter. During this state, the sum of two capacitor voltage is greater than the input battery voltage (VC1 + VC2 > VB) and the energy stored in the capacitor is transferred to the inductor and the diode is off. Hence, the ZSI gains the voltage boost capability.

The voltage equations are obtained by considering the ZSI as a symmetrical network [1 and 2]

$$V_{C1} = V_{C2} = V_C \tag{2}$$

$$V_{L1} = V_{L2} = V_L \tag{3}$$

The capacitors and inductors voltages are equal which is given by,

$$V_C = V_L \tag{4}$$

The input voltage to the Z-source network Vd is given by,

$$V_d = 2V_C \tag{5}$$

The input voltage Vin to the inverter is given by,

$$V_{in} = 0 \tag{6}$$

C. Mode 3 – Active state or non shoot through state

The non shoot through state of the ZSI is the one of the six active switching states of the ZSI similar to that of traditional VSI. When the ZSI is working in non shoot through states during time interval Tactive, the diode D is on, and the H-bridge inverter can be considered as a current source Iin.

The input battery voltage VB to the Z-source network is given by,

$$V_B = V_d = V_C + V_L \tag{7}$$

From Equation (7), the inductor voltage VL is given by,

$$V_L = V_B - V_C \tag{8}$$

The Z-source inverter input voltage is given by,

$$V_{in} = V_C - V_L \tag{9}$$

By substituting Equation (8) in Equation (9), the ZSI input voltage is given by,

$$V_{in} = 2\,V_C - V_B \tag{10}$$

The average voltage of inductor L1 (or L2) over one switching period in steady state operation is zero [1]. From Equations (4) and (8), the inductor voltage VL is given by,

$$V_L = (V_B - V_C)\,T_{active} + V_C\,T_{shoot} = 0 \tag{11}$$

From the above Equation (11), the capacitor voltage VC is given by,

$$V_C = \frac{T_{active}}{T_{active} - T_{shoot}} V_B \tag{12}$$

By substituting Equation (12) into Equation (10)

$$V_{in} = \frac{T_s}{T_{active} - T_{shoot}} V_B = B.V_B \tag{13}$$

The increase in inverter output voltage depends upon this boost factor (B), and it is given by,

$$B = \frac{T_s}{T_{active} - T_{shoot}} \tag{14}$$

where, B is the boost factor

Boost factor is defined as the ratio of switching time period to the difference in duration between active state time and the shoot through time period. Boost factor value is always greater than or equal to one. By adjusting the boost factor, the output voltage of the Z-Source inverter can be increased or decreased. The Equation (14) can be rewritten as,

$$B = \frac{1}{1 - 2\frac{T_{shoot}}{T_s}} = \frac{1}{1 - 2\,d} \tag{15}$$

where, d is the shoot through duty ratio

Hence from the Equation (15), the boost factor depends on the duty ratio (d). The duty ratio (d) is given by,

$$d = \frac{T_{shoot}}{T_s} \tag{16}$$

From the Equation (12) & (15), the capacitor voltage VC is given by,

$$V_C = \frac{1-d}{1-2d} V_B \tag{17}$$

If the voltage across the filter inductor is ignored, the output peak voltage of the inverter is given by,

$$V_{ac} = M\,\frac{V_{in}}{2} \tag{18}$$

where, M is the modulation index

By substituting the Equation (13) into Equation (18),

$$V_{ac} = M\,\frac{B.V_B}{2} = M\,B\,\frac{V_B}{2} = B_B\,\frac{V_B}{2} \qquad (19)$$

where, BB is the Buck –Boost factor and it is given by,

$$B_B = M\,.\,B \qquad (20)$$

The voltage gain G of the ZSI is the ratio of the inverter output voltage to the input voltage and it is given by,

$$G = \frac{V_{ac}}{V_B/2} = M\,B = B_B \qquad (21)$$

Thus, any desired output voltage can be obtained by properly selecting the boost factor and the modulation index regardless of the DC voltage.

IV. PWM TECHNIQUES FOR ZSI

The Z-source inverter has an additional zero state, called shoot through state. This shoot through period distribution in the switching waveforms is the key factor to control the output voltage of ZSI. The dc link voltage boost, controllable range of ac output voltage, voltage stress across the switching devices and harmonic profile of the ac output voltage and current are based on the control algorithms adapted to insert the shoot through period . There are number of control algorithms which have been presented in recent years. The methods used for controlling the shoot through state are simple boost PWM control (SB PWM), maximum boost PWM control (MB PWM), third harmonic injected maximum constant boost PWM control (THIMCB WM), Space Vector Modulation [10]. In this paper, the two PWM control algorithms SB PWM and MB PWM are explained elaborately and their performance characteristics are investigated. The insertion of shoot through time gets varied in the three PWM control algorithms. Hence, by implementing the PWM control algorithms boost factor is increased by adjusting the shoot through time.

A. Simple boost PWM control (SB PWM) algorithm

The block diagram of SB PWM controller for the impedance source inverter topologies is shown in Fig 2. The sinusoidal reference signals VR, VY, VB and two constant DC voltages Vpos and Vneg are compared with the triangular carrier wave Vtri by using the comparators to generate the firing pulses with the shoot through state. The amplitude of the two straight lines is equal to or greater than the peak amplitude of the sinusoidal reference wave. The comparator 1 compares the reference signals with the triangular carrier signals and generates the active state pulses for the inverters. The comparator 2 generates the shoot through state, when the triangular carrier wave is greater than the upper envelope Vpos or lower than the bottom envelope Vneg. The output of the comparator 1 and 2 is added by the adder to generate the firing pulses with active state and shoot through state [11].

For this simple boost control algorithm, the obtainable shoot through duty ratio decreases with the increase of modulation index (M). Due to this voltage stress across the switches is high. The maximum shoot through duty ratio of the simple boost PWM control algorithm is limited to 1-M. Thus the shoot through duty ratio reaches zero when the modulation index is one. In order to produce an output voltage with high voltage gain, a small modulation index M has to be used. The small modulation index M results in high voltage stress across the switches.

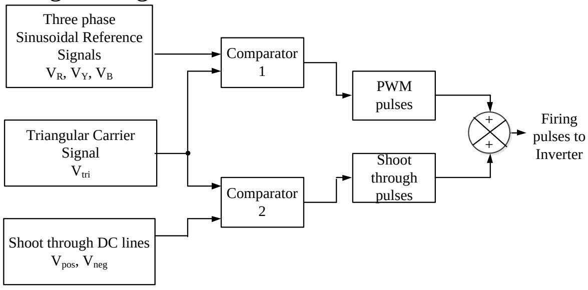

Fig 2. Simple boost PWM controller

By using this simple boost PWM control algorithm, the voltage stress across the switching devices is somewhat high, which will restrict the obtainable voltage gain.

B. Maximum Boost PWM control (MB PWM) algorithm

The maximum boost PWM algorithm is implemented to obtain the maximum voltage boost in the Z-source based inverters. In the SB PWM algorithm, in order to produce an output voltage with high voltage gain, a small modulation index (M) has to be used, hence the voltage stress across the switches is increased. The voltage stress across the switching devices should be reduced in order to increase the voltage gain in the MB PWM control [12].

The Fig 3. depicts the maximum boost PWM controller for the impedance source inverters. The reference signals and triangular carrier waveform are compared to produce the active state pulses, this is obtained from the comparator 1. The comparator 2 generates the shoot through state, when the triangular carrier wave Vtri is greater than the maximum of sinusoidal reference signals VR, VY, VB or smaller than the minimum of the sinusoidal reference signals. The active state signals and shoot through state signals obtained from the comparator 1 and 2 are added to generate the firing pulses for the impedance source inverters. The shoot through duty cycle is not constant and varies each cycle [12].

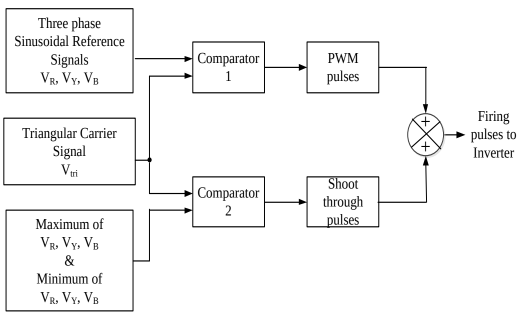

Fig 3. Maximum boost PWM controller

This control algorithm maintains the six active states unchanged, and all zero states are turned into shoot through zero states. Thus for any given modulation index (M), maximum shoot through time (Tshoot) and boost factor (B) is obtained without affecting the output waveform [12].

Fig 4. shows the maximum obtainable voltage conversion ratios (G) for ZSI Vs modulation index (M) by using the two PWM control algorithms. The MB PWM control gives the high voltage gain but the voltage stress across the switching devices is high.

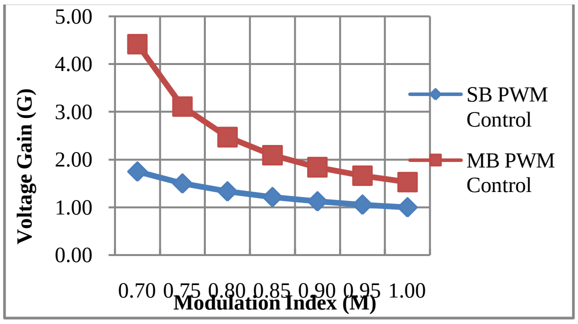

Fig 4. Modulation Index (M) Versus Voltage Gain (G)

The Table 1 shows the comparison of the three PWM control algorithms used for ZSI. The various operating parameters like shoot through duty ratio d, boost factor B, voltage gain G and voltage stress Vstress with respect to the modulation index M are tabulated in Table 2.

Table 1 Parameters of ZSI with different PWM control

PWM control algorithm	**Shoot through duty ratio d**	**Boost factor B**	**Voltage gain G**	**Voltage stress V_{stress}**
SB PWM	$1 - M$	$\frac{1}{2M - 1}$	$\frac{M}{2M - 1}$	$\frac{1}{2M - 1} V_B$
MB PWM	$\frac{2\pi - 3\sqrt{3}M}{2\pi}$	$\frac{\pi}{3\sqrt{3}M - \pi}$	$\frac{\pi M}{3\sqrt{3}M - \pi}$	$\frac{\pi}{3\sqrt{3}M - \pi}$

V. Simulation Resuts and Discussion

The simulation model of Z-Source inverter is implemented using MATLAB/SIMULINK software and the results are analyzed. The performance investigation of ZSI by using two PWM algorithms SB PWM and MB PWM are presented in this section. The output voltage, current and THD values are analysed for the two PWM algorithms by maintaining the constant battery voltage and duty ratio. The common electrical system parameters used in the performance analysis of ZSI are given in Table 2.

Table 2 System parameters used for simulation

Parameters	**Specification**
Battery Voltage	36 V
Z-Source Inductors L_1 and L_2	1.5 mH
Z-Source Capacitors C_1 and C_2	1000 µF
Filter Inductor	20 mH
Filter Capacitor	250 µF
Load	4 kW
Switching Frequency	1 kHz

A. *Simulation Results of ZSI with SB PWM algorithm*

To examine the performance of ZSI, the MATLAB/SIMULINK simulation is carried out with the battery voltage of 36V. The modulation index used in this SB PWM control algorithm is 0.7, which gives the duty ratio of 0.3. The boost factor value is 2.5 for the chosen modulation index of 0.7.

The simulation results of the inverter output phase-phase voltage and the inverter output current are shown in Fig 5 and 6 respectively. When the modulation index is 0.7, the obtained inverter input voltage is 90V and the corresponding phase voltage is 32V. The inverter output phase-phase voltage is 55 V which is $\sqrt{3}$ times the phase voltage. These theoretical calculations are quite consistent with the simulation results.

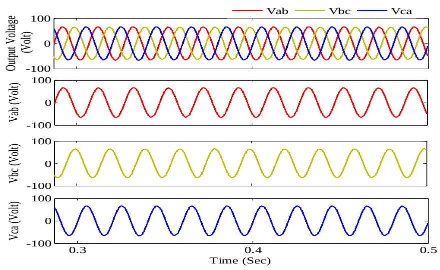

Fig 5. ZSI output voltage with SB PWM

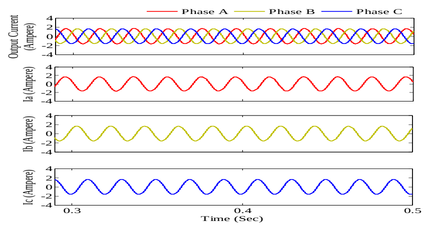

Fig 6. ZSI output current with SB

B. *Simulation Results of ZSI with MB PWM*

The performance of ZSI is analyzed by using maximum boost PWM control algorithm. In this MB PWM control algorithm all the zero states are converted into shoot through state. Hence it gives the maximum voltage boost. The modulation index used in this MB PWM control algorithm is 0.85, which gives the duty ratio of 0.3. The capacitor voltage VC is boosted to 62V and the inverter input voltage is 89V, when the battery voltage is 36V and modulation index is 0.85. The boosted inverter input voltage is 89V and the corresponding output phase voltage obtained is 38V. The ZSI output phase-phase voltage is 65V. The output voltage and current are given in Fig 7 and 8.

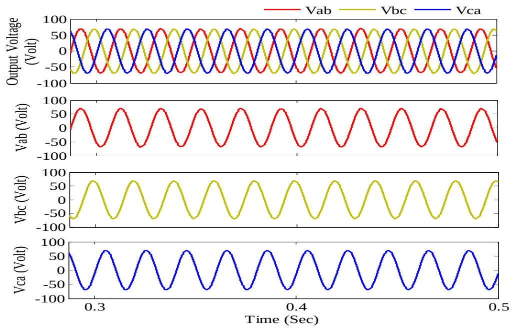

Fig 7. ZSI output voltage with MB PWM

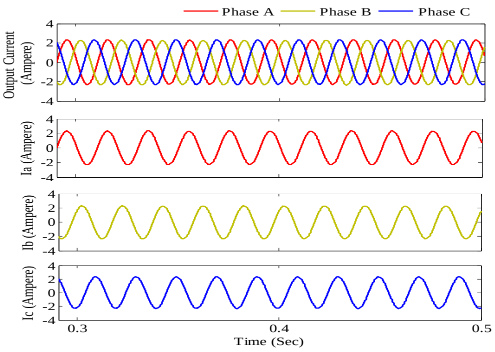

Fig 8. ZSI output current with MB

The numerical comparison of boost factor, input voltage, output voltage, output current, Total Harmonic Distortion (THD in %) obtained from the ZSI by implementing the SB PWM and MB PWM control is shown in Table 3.

Table 3. Simulation results of ZSI with SB and MB PWM

Parameters	**SB PWM**	**MB PWM**
Modulation Index M	0.7	0.85
Duty ratio	0.3	0.3
Battery Voltage V_B	36 V	36 V
Boost Factor B	2.5	2.46
Capacitor voltage V_C	63V	62V
Input voltage V_{in}	90 V	89 V
Output phase-phase voltage	55 V	65 V
Output phase voltage	32 V	38 V
Output phase-phase voltage THD	5.68%	5.77%
Output phase voltage THD	3.65%	3.8%
Output current THD	3.23 %	3.41%

VI. CONCLUSION

The operating modes and equivalent circuits of Z-source inverter have been discussed in this chapter. The three PWM techniques are elaborately discussed. The mathematical expressions for shoot through duty ratio, boost factor, voltage gain, Z-source capacitance voltage, DC link voltage (inverter input voltage) and output voltage for the three PWM techniques are presented. The simulation waveforms for the three PWM techniques are presented for the validation of the theoretical analysis. The numerical comparison of three PWM techniques is also discussed. From the results comparison, the voltage boost in THIMCB PWM control is higher than SB PWM and MBPWM control. The output voltage and current THD of the THIMCB PWM control is less.

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