A Comparative Study of PWM Strategies for Cascaded Z-Source Multilevel Inverter

Dr. R. Seyezhai
Associate Professor
Department of EEE, SSN College of Engineering, India
seyezhair@ssn.edu.in

Dr. B. L. Mathur
Professor
Department of EEE, SSN College of Engineering, India

A. Shanmuga Priyaa
Final Year M.E. (PED)
Department of EEE, SSN College of Engineering, India
shan30121988@gmail.com

Abstract - Multilevel Inverter (MLI) is an effective topology for high voltage DC-AC conversion. It synthesizes a desired voltage waveform from several levels of DC voltages. But the main disadvantage of MLI is its output voltage amplitude is limited to DC source voltage summation. Therefore, a five-level symmetric cascaded multilevel inverter based Z-source inverter has been proposed in this paper. In the proposed topology output voltage amplitude can be boosted with Z network shoot-through state control. This paper focuses on Unipolar, bipolar and Third harmonic injection PWM strategies for the proposed topology. The performance of Z-Source MLI has been analyzed for various modulation strategies. A simulation model of conventional cascaded multilevel inverter and Z-source MLI has been built in MATLAB/SIMULINK.

Keywords - Cascaded Z-source MLI, Third harmonic PWM, THD, Voltage Gain & Voltage stress.

I. INTRODUCTION

Multilevel inverters (MLI) have emerged as the solution for working with higher voltage levels. Multilevel inverters include an array of power semiconductors and capacitor voltage sources, the output of which generate voltages with stepped waveforms. The commutation of the switches permits the addition of the capacitor voltages, which reach high voltage at the output, while the power semiconductor must withstand only reduced voltages. By synthesizing the AC output terminal voltage from several levels of DC voltages, staircase output waveform can be produced. This allows for higher output voltage and simultaneously lowers the voltage stress in the switch. Multilevel inverter is used for applications such as large induction motor drives, UPS systems and flexible AC transmission systems (FACTS). Multilevel inverters output voltage amplitude is limited to DC source voltage summation. For the boost or buck of multilevel output voltage the other converters as a DC/DC converter is needed. Occurring of short circuit can destroy multilevel inverters. To solve these problems, multilevel inverter based Z-source inverter is proposed in this paper.

The Z-source inverter utilizes Z impedance network between the DC source and inverter circuitry to achieve buck-boost operation. The Z-source inverter, unlike traditional inverters can utilize shoot-through states to boost the input dc voltage of inverter switches when both switches in the same phase leg are on. The Z-Source inverters with respect to traditional inverters are lower cost, reliable, lower complexity and higher efficiency. In this paper, a cascaded five level Z-Source inverter is proposed for renewable energy systems. The proposed topology employs Z network between the DC source and inverter circuitry to achieve boost operation. The output voltage of proposed inverter can be controlled using modulation index and shoot through state.

Cascaded Z-Source Multilevel inverter is analyzed with various modulation techniques. Modulation techniques employed are Unipolar, Bipolar and Third harmonic injection PWM techniques. A comparative analysis of modulation techniques has been presented in terms of Total Harmonic Distortion (THD) and Total Voltage Stress. The performance of Z-Source Multilevel inverter is compared with the conventional cascaded multilevel inverter. Simulations of the circuit configuration of various modulation strategies have been performed in MATLAB/SIMULINK.

II. CASCaded Z-SOURCE MULTILEvel INVERTer

The circuit diagram of cascaded Z-Source five-level inverter is shown in Fig.1. It consists of a series single phase H bridge inverter units, Z impedances and DC voltage sources. DC sources can be obtained from batteries, fuel cells, solar cells [1]. Each H-bridge Z-Source inverter can generate three different output voltage +Vin, 0, -Vin. Output voltage can be higher than the input voltage when boost factor, B>1. The number of output voltage levels, m in this topology is given by (n-1)/2, where n is the number of Z impedances or DC voltage sources. This topology has an extra switching state: shoot through state as compared to cascaded H-bridge inverters. During the shoot-through state, the output voltages of Z networks are zero.
Fig.1. Five-level cascaded Z-source Multilevel Inverter

Circuit operation consists of two modes namely shoot-through and non shoot-through states [2]. In Shoot-Through (ST) switching state of Z-Source MLI, upper and lower bridges of the same leg is turned on having the output voltage of zero. During non shoot-through state opposite pairs of legs of both the bridge conducts. In ST state the two inductors are being charged by the capacitors and in Non-Shoot-Through (NST) states the inductors and input DC source transfer energy to the capacitors and load. This process is similar to the boost converter. Output voltage depends on the boost factor,

\[ B = \frac{1}{1 - \frac{2(V_{ca} - V_p)}{V_{ca}}} = \frac{1}{1 - \frac{2T_{sh}}{T}} \]  

where \( V_{ca} \) represents the peak value of the triangular waveform, \( V_p \) represents the Amplitude of the constant, \( T_{sh} \) represents the Total shoot-through state period and \( T \) represents the period of switching.

III. MODULATION STRATEGIES

The modulation control schemes for the multilevel inverter can be divided into two categories, fundamental switching frequency and high switching frequency Pulse Width Modulation (PWM). Further, the high frequency PWM is classified as multilevel carrier-based PWM, selective harmonic elimination and multilevel space vector PWM [3]. The most popular and simple high frequency switching scheme for multilevel inverter is Multi-Carrier-PWM (MCPWM). MCPWM is employed for the proposed topology.

1. Unipolar PWM

Among the several PWM techniques reported in the literature [4], the simplest method is Unipolar PWM which is implemented for Z-source MLI. In this method four phase shifted carrier triangular signals are compared with the two modulating sinusoidal signal to produce switching PWM pulses as shown in Fig.2. This method employs two straight lines that are greater than or less than the peak value of the reference sinusoidal signal to control the shoot-through duty ratio. Intersection between the modulating sinusoidal signals and the carrier signal defines the switching instant of the PWM pulses. Inverter operates in shoot-through whenever the triangular carrier signal is higher than the positive straight line or lower than the negative straight line. The frequency of the modulating signal is taken as 50Hz. The frequency of the triangular signal can be calculated by Frequency modulation index, \( M_f \) which is given by,

\[ M_f = \frac{f_c}{f_o} \]  

Where \( f_c \) is the frequency of the carrier signal and \( f_o \) is the frequency of sinusoidal and modulating signals. \( M_f \) should be multiples of three and odd integer to ensure the output PWM waveform having less harmonic distortion and total harmonic distortion [5]. Here we take \( m_f \) as 21 and the frequency of the triangular carrier signal is 1050Hz. Based on PWM pulse, the upper and lower bridge switches are turned on/off depending on whether the modulating waveform is greater or lower than the carrier waveform. Fig.3 shows the gating pattern for unipolar PWM technique.

Fig.2. Unipolar PWM technique

Gating pattern for unipolar PWM technique is shown in Fig.3.
2. Bipolar PWM Technique

In this method four phase shifted carrier triangular signals are compared with single modulating sinusoidal signal as shown in Fig.4. This method employs two straight lines that are greater than or less than the peak value of the reference sinusoidal signal to control the shoot-through duty ratio. Intersection between the modulating sinusoidal signals and the carrier signal defines the switching instant of the PWM pulses. Inverter operates in shoot-through whenever the triangular carrier signal is higher than the positive straight line. In Bipolar PWM, switches of the opposite pairs of legs of both bridges of Z-source cascaded multilevel inverter are switched simultaneously [6], [7]. Total harmonic distortion is higher in Bipolar than in Unipolar. In Bipolar, for the low fundamental voltage there are carrier frequency harmonics and for the high fundamental voltage there are not only the carrier frequency harmonics but also the harmonics of order $m\pm3$, $3m\pm2$ etc. Compared to Unipolar PWM, Bipolar PWM avoids leakage current between source and ground [8], [9].

3. Third Harmonic Injection PWM

In general, the total harmonic distortion obtained for Z-source multilevel inverter waveform is considered as unacceptable. A simple third harmonic injection method is therefore presented to provide the waveform with high quality. The third harmonic injection PWM is similar to the Unipolar and Bipolar PWM method. The difference is that the reference ac waveform is not sinusoidal but consists of both fundamental component and third harmonic component as shown in Fig.5. The sinusoidal reference signal can be injected by a third harmonic with a magnitude equal to 25% of the fundamental. As a result, the peak-to-peak amplitude of the resulting reference function does not exceed the DC supply voltage $V_s$, but the fundamental component is higher than the available supply $V_s$. This eliminates third and multiples of third order harmonics which leads to reduction in Total Harmonic Distortion [10].

IV. Simulation Results

Fig.6. shows Matlab / Simulink of Z-Source cascaded MLI using Unipolar PWM with boost factor = 1.25, $M_a=0.8$, RL Load where $R=50$ Ω and $L=24mH$, Input voltage $V_{dc}=75V$, Z impedances, $L_1=L_2=L_3=L_4=L=40mH$ and $C_1=C_2=C_3=C_4=6600\mu F$. Simulink circuit is shown with LC filter having $L=30mH$ and $C=150\mu F$.
The simulation results of load voltage and load current waveforms for unipolar PWM technique without & with filter are shown in Figs. 7, 8 & 9.

The simulation results of load voltage and load current waveforms for bipolar PWM technique without & with filter are shown in Figs. 10, 11 & 12.
The simulation results of load voltage and load current waveforms for third harmonic injected PWM technique without & with filter are shown in Figs. 13, 14 & 15.

V. PERFORMANCE PARAMETERS OF FIVE-LEVEL CASCaded Z-SOURCE MLI

Performance parameters of Z-Source multilevel Inverter are analyzed for various modulation index for given boost factor. They are Total Harmonic Distortion, inductor current ripple of Z-Source inverter, capacitor voltage ripple of Z-Source inverter, voltage gain and voltage stress.

4.1 Total Harmonic Distortion (THD)

Total Harmonic Distortion of five level Z-Source inverter is analyzed and compared for modulation strategies - Unipolar PWM, bipolar PWM and Third order harmonic injection PWM. THD is calculated for various modulation index values and the comparison is shown in Fig. 16.
4.2 Inductor Current Ripple

Inductor current ripple is calculated across the inductor of Z-source inverter. Inductor current ripple is shown in Table I for various modulation strategies that changes with variation in modulation indices.

<table>
<thead>
<tr>
<th>Ma</th>
<th>Inductor Current Ripple For Bipolar PWM</th>
<th>Inductor Current Ripple For Unipolar PWM</th>
<th>Inductor Current Ripple For Third Order Harmonic Injection PWM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>0.5263</td>
<td>0.5062</td>
<td>0.5</td>
</tr>
<tr>
<td>0.73</td>
<td>0.7096</td>
<td>0.4489</td>
<td>0.5631</td>
</tr>
<tr>
<td>0.67</td>
<td>0.81</td>
<td>0.5698</td>
<td>0.7</td>
</tr>
<tr>
<td>0.56</td>
<td>1.5</td>
<td>1.32</td>
<td>1.20</td>
</tr>
</tbody>
</table>

4.3 Capacitor Voltage Ripple

Capacitor voltage ripple is calculated across the capacitor of Z-source inverter. Capacitor voltage ripple is shown in Table II for various modulation strategies that changes with variation in modulation indices.

<table>
<thead>
<tr>
<th>Ma</th>
<th>Capacitor Voltage Ripple For Bipolar PWM</th>
<th>Capacitor Voltage Ripple For Unipolar PWM</th>
<th>Capacitor Voltage Ripple For Third Harmonic Injection PWM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>0.0392</td>
<td>0.0221</td>
<td>0.0188</td>
</tr>
<tr>
<td>0.73</td>
<td>0.0162</td>
<td>0.0210</td>
<td>0.0120</td>
</tr>
<tr>
<td>0.67</td>
<td>0.0105</td>
<td>0.0206</td>
<td>0.0091</td>
</tr>
<tr>
<td>0.56</td>
<td>0.0045</td>
<td>0.0284</td>
<td>0.0026</td>
</tr>
</tbody>
</table>

4.4 Voltage Gain (G)

Voltage Gain, G is calculated for various modulation strategies. In Fig. 17, voltage gain is compared with different modulation indices for all modulation techniques. Voltage gain, G is given by,

\[ G = \frac{2V_{ac}}{V_{in}} \]  

where, \( V_{ac} \) = RMS value of output voltage and \( V_{in} \) = Input voltage

4.5 Voltage Stress

Voltage stress is calculated with voltage gain for various modulation techniques. Voltage Stress is calculated from voltage gain. Voltage Gain is given by,

\[ \text{Voltage Stress} = 2 - \frac{1}{G} \]  

where, \( G \) = Voltage Gain

Figs. 18, 19 & 20 shows variation of voltage stress with voltage gain (G) for all three techniques.
From the simulation results it is observed that Third harmonic injection PWM technique gives high voltage gain and reduced THD. Inductor current ripple and capacitor voltage ripple of Z-Source cascaded inverter are also reduced. From the results, it is found that Z-MLI with third harmonic injection PWM provides a higher RMS value of the output voltage, higher voltage gain, reduced voltage stress and avoids the intermediate boost DC-DC converter. Therefore, Third harmonic injection PWM technique is preferred for the proposed topology.

VI. COMPARISON WITH CONVENTIONAL CASCaded MLI

Output voltage and other parameters are compared between Z-Source MLI and conventional cascaded MLI in Table -III. Third harmonic injection PWM technique is preferred for the topology.

TABLE –III : COMPARISON BETWEEN Z-SOURCE CASCaded MLI AND CONVENTIONAL CASCaded MLI

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>Z-SOURCE CASCaded MLI</th>
<th>CONVENTIONAL CASCaded MLI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation index</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>RMS value of fundamental output voltage</td>
<td>217.6</td>
<td>132.6</td>
</tr>
<tr>
<td>RMS value of output voltage</td>
<td>214.96</td>
<td>130.8</td>
</tr>
<tr>
<td>Boost factor</td>
<td>1.25</td>
<td>1</td>
</tr>
<tr>
<td>THD</td>
<td>1.8</td>
<td>1.3</td>
</tr>
</tbody>
</table>

From the Table III, rms value of output voltage of Z-Source MLI is greater than conventional cascaded MLI. So Unlike Z-Source MLI conventional cascaded MLI needs two converters for boosting the output voltage [13].

VII. CONCLUSION

Z-Source cascaded multilevel inverter gives higher output voltage through its z network. Boost operation is achieved by the shoot through state of Z-Source MLI. THD for Unipolar modulation technique is less when compared to Bipolar technique. Since by Third Harmonic Injection PWM technique third and multiples of third harmonics are eliminated its THD is much less than Unipolar and Bipolar modulation techniques. Also inductor current ripple and capacitor voltage ripple is less in Third Harmonic Injection PWM modulation than others. THD is found to increase with decrease in modulation index, Ma. And THD of 5-level Z-Source cascaded MLI is greater than conventional cascaded MLI. Voltage gain and voltage stress increases for PWM techniques in the order of Bipolar PWM, Unipolar PWM and Third Harmonic Injection PWM. Unlike Z-Source MLI conventional cascaded MLI needs two converters for boosting the output voltage.

ACKNOWLEDGMENT

The authors wish to thank the management of SSN institutions for providing the computational facilities to carry out this work.

REFERENCES


**AUTHOR’S PROFILE**

**Dr. R. Seyezhai**

obtained her B.E. (Electronics & Communication Engineering) from Noorul Islam College of Engineering, Nagercoil in 1996 and her M.E in Power Electronics & Drives from Shannmuga College of Engineering, Thanjavur in 1998 and Ph.D. from Anna University, Chennai, in 2010. She has been working in the teaching field for about 13 Years. She has published 75 papers in the area of Power Electronics & Drives. Her areas of interest include SiC Power Devices & Multilevel Inverters.

**Dr. B. L. Mathur**

obtained his B.E. (Electrical Engineering) from University of Rajasthan, in 1962 and his M.Tech. in Power Systems from IIT, Bombay in 1964. He completed his Ph.D. in 1979 from IISc, Bangalore. His Ph.D. thesis was adjudged as the best for application to industries in the year 1979 and won gold medal. He has been working in the teaching field for about 44 Years. He takes immense interest in designing Electronic circuits. He has published 50 papers in National and International journals and 85 in National and International conferences. His areas of interest include Power Devices, Power Converters, Computer Architecture and FACTS.

**A. Shanmuga Priyaa**

obtained her B.E. (Electrical & Electronics Engineering) from St. Josephs College of Engineering, Chennai in 2010 and presently doing her IIInd year M.E. in Power Electronics & Drives in SSN College of Engineering, Chennai. Her areas of interest include Power electronics & Multilevel Inverters.