INVESTIGATION OF PERFORMANCE PARAMETERS FOR ASYMMETRIC MULTILEVEL INVERTER USING HYBRID MODULATION TECHNIQUE

Dr.R.Seyezhai *
*Associate Professor, Department of EEE, SSN College of Engineering, Chennai.

Abstract

The performance of multilevel inverter (such as switching loss and harmonics) is mainly decided by its modulation strategies. This paper focuses on a hybrid modulation strategy for asymmetric cascaded seven-level inverter. The proposed technique combines the fundamental frequency switching scheme and Variable Frequency Inverted Sine Pulse Width Modulation (VFISPWM). A detailed study of the modulation technique has been carried out through MATLAB/SIMULINK for switching losses and Total Harmonic Distortion (THD). A comparative evaluation between hybrid modulation strategy and the conventional Phase Disposition (PD) PWM method has been presented in terms of output voltage quality, power circuitry complexity, Distortion Factor (DF) and THD. The performance of asymmetric cascaded MLI with the proposed modulation strategy has been studied both for linear and non-linear loads and the simulation results have been verified experimentally.

Keywords: Fundamental frequency switching, VFISPWM, THD, & DF

1. Introduction

Recently, MultiLevel Inverter (MLI) topology is of paramount importance for high voltage and high power applications. Several topologies of MLI have been reported in the literature. But this paper presents an asymmetric cascaded multilevel inverter employing two unequal DC sources to generate seven-level output. 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 [1]. The most popular and simple high frequency switching scheme for multilevel inverter is multi-carrier-PWM (MCPWM). It can be categorized into two groups: Carrier Disposition methods (CD) and phase shifted (PS) methods [2]. Among the carrier disposition methods, Phase Disposition (PD) PWM technique is normally employed as the carriers need minimal amounts of alteration since they are all in phase with each other. This paper focuses on hybrid modulation strategy for MLI. The proposed technique combines the fundamental frequency switching scheme and variable frequency inverted sine pulse width modulation (VFISPWM) [3]. The inverted sine PWM has a better spectral quality and a higher fundamental voltage compared to the triangular based PWM. But the main drawback is the marginal boost in the magnitude of lower order harmonics and unbalanced switch utilization. This is overcome by employing variable frequency inverted sine carrier signals which leads to reduced switching losses and low harmonic content.

The analysis and impact of the hybrid modulation technique is presented in detail and the performance is verified by simulation. A comparison between the hybrid modulation strategy and the conventional Phase Disposition (PD) PWM method is also presented in terms of output voltage quality, power circuitry complexity, THD and switching losses. Simulation of the single-phase seven-level asymmetric cascaded
multilevel inverter is performed using MATLAB/SIMULINK. The voltage and current waveforms are obtained for different loading conditions (linear and non-linear loads). This paper also describes the design and construction of a single-phase seven-level MLI prototype to verify the proposed hybrid modulation PWM scheme.

2. Single-phase Asymmetric Cascaded Multilevel Inverter

The cascaded multilevel inverter with separate DC sources can fit many of the needs of all electric vehicles because it can use on board batteries or fuel cells to generate a nearly sinusoidal voltage waveform to drive the main vehicle traction motor. Normally, each phase of a three-phase cascaded multilevel inverter requires “n” DC sources for 2n+1 level [4]. For many applications, multiple DC sources are required demanding long cables and this could lead to voltage unbalance among the DC sources [5]. With an aim to reduce the number of DC sources required for the cascaded multilevel inverter, this paper focuses on an asymmetric topology which uses only two DC sources to generate seven-level output. The proposed topology consists of two H-bridges as shown in Fig.1. By appropriately opening and closing the switches of H1, the output voltage V1 can be made equal to - Vdc, 0, + Vdc. Similarly the output voltage V2 of the second bridge H2 can be made equal to - 0.5V dc, 0 , 0.5V dc. Therefore, the output voltage of the MLI have the values of -1.5 Vdc, -Vdc, -0.5Vdc, 0, 0.5Vdc, Vdc and 1.5Vdc as shown in Fig.2.

![Fig.1 Single-phase Asymmetric cascaded multilevel inverter](image.png)
3. Hybrid Modulation Strategy for asymmetric cascaded multilevel inverter

The proposed modulation technique employs fundamental frequency switching for the bridge H1 (Fig.1) where the switch turns on and off once per cycle. This strategy makes the H1 bridge to operate with the lowest possible switching loss. For bridge H2, VFISPWM is applied which increases the fundamental component resulting in lower THD. The output voltage of MLI is given by

$$V_o = V_1 + V_2$$  \hspace{1cm} (1)

where, $V_1$ represents the output voltage of bridge H1, $V_2$ represents the output voltage of bridge H2.

The desired output voltage of MLI is given by

$$V_o(t) = V_{o,amp} \sin(\omega t)$$  \hspace{1cm} (2)

where, $V_{o,amp}$ represents the amplitude of the desired output voltage.

Figure 3 describes how the desired output voltage waveform is synthesized using bridges H1 and H2. Bridge H1 is supplied by $V_{dc}$ and generates a rectangular waveform which is at the same frequency of the reference [6,7]. Equation (3) describes the relationship between the amplitude of the desired output voltage and the DC voltage level of the bridge H1.

$$V_{o,amp} = \frac{4V_{dc}}{\pi} \cos \alpha$$  \hspace{1cm} (3)

where, ‘$\alpha$’ represents the conduction angle of bridge H1.
The conduction angle ‘\(\alpha\)’ is determined using the equation given by

\[
\cos n\alpha = m \tag{4}
\]

where, ‘m’ is given by

\[
m = \frac{V_1}{4 \sqrt{\pi}} V_{dc} \tag{5}
\]

With this definition of the parameter \(m\), the modulation index \(m_a\) is given by

\[
m_a = \frac{m}{s} \tag{6}
\]

where ‘s’ is the number of DC sources.

By using equation (4) the value of ‘\(\alpha\)’ is obtained for various values of modulation index as shown in Table 1.
Table 1 Switching angle Vs modulation index for bridge H1

<table>
<thead>
<tr>
<th>Modulation index (m_a)</th>
<th>Switching angle (α) (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>64.18</td>
</tr>
<tr>
<td>0.7</td>
<td>59.57</td>
</tr>
<tr>
<td>0.8</td>
<td>54.47</td>
</tr>
<tr>
<td>0.9</td>
<td>54.76</td>
</tr>
<tr>
<td>1.0</td>
<td>48.98</td>
</tr>
<tr>
<td>1.1</td>
<td>41.06</td>
</tr>
<tr>
<td>1.12</td>
<td>36.62</td>
</tr>
<tr>
<td>1.15</td>
<td>33.61</td>
</tr>
<tr>
<td>1.2</td>
<td>28.72</td>
</tr>
</tbody>
</table>

Choosing m_a = 0.90 in this work, bridge H1 output is synthesized by fundamental switching and the simulated waveform is shown in Fig.1.

3.1 VFISPWM Technique for Bridge H2

The proposed control strategy replaces the conventional triangular based carrier waveform by inverted sine wave which has a better spectral quality and a higher fundamental output voltage without any pulse dropping [8]. However, the fixed frequency carrier based PWM affects the switch utilization in multilevel inverters. In order to balance the switching duty among the various levels in inverters, a variable frequency carrier based PWM has been suggested [9]. The proposed novel method combines the advantage of inverted sine and variable frequency carrier signals. The VFISPWM method provides an enhanced fundamental voltage, lower THD and minimizes the switch utilization among the bridges in inverters. The number of active switching among the bridges is balanced by varying the carrier frequency based on the slope of the modulating wave in each band. The frequency ratio for each band should be set properly for balancing the switching action for all bridges. Using the slope values of the carrier bands, the new frequencies are calculated. The number of switching actions is balanced for all the switches in bridge H2 using the VFISPWM technique. The band dwell time of the modulating wave in each carrier and the frequency ratio (m_f) is calculated as shown in Table 2.

Table 2 Calculation of the dwell time of the modulating wave, frequency and Nsw for VFISPWM

<table>
<thead>
<tr>
<th>Carrier band</th>
<th>T_{band} (radians)</th>
<th>( m_f )</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1 – C_1</td>
<td>1.081</td>
<td>79</td>
<td>3950</td>
</tr>
<tr>
<td>Band 2 – C_2</td>
<td>1.241</td>
<td>69</td>
<td>3450</td>
</tr>
<tr>
<td>Band 3 – C_3</td>
<td>2.677</td>
<td>33</td>
<td>1650</td>
</tr>
</tbody>
</table>
The gating signals for the hybrid seven level inverter employing the VFISPWM technique is generated using a digital logic. The comparator output is given to a 3-input XOR gate that generates gating signals to the corresponding switches. The proposed VFISPWM scheme is simulated in MATLAB and the gating signals generated are shown in Fig. 5.

Fig. 4 Carrier and reference waveforms for VFISPWM (for clarity of waveforms the carrier frequency is scaled down by 20 times)

Fig. 5 Switching pattern for hybrid modulation method
The simulated output voltage waveform for bridge H2 using VFISPWM technique is shown in Fig.6.

![Waveform of Bridge H2 (VFISPWM)](image)

**Fig.6 Output voltage of bridge H2**

### 5.3 Simulation Results

The simulated load voltage and load current (RL load) of asymmetric cascaded MLI employing hybrid modulation is shown in Fig.7.

![Load Voltage and Current of MLI](image)

**Fig.7 Output load voltage and load current of MLI**

The performance of MLI for non-linear load (rectifier) is studied. Rectifier load comprises of a full-bridge rectifier, choke (L_{choke}), filter capacitor (C_L) and load resistor (R_L). The choke or power factor correction
inductor has been included as this is commonly used in power supplies to reduce the rate of change in load current \( (\text{di}_{\text{load}}/\text{dt}) \) thus improving inverter performance. The SIMULINK model of rectifier load is shown in Fig.8.

Fig.8. SIMULINK model of rectifier load

Fig.9 shows the supply current obtained using the SIMULINK model of rectifier load.

The FFT spectrum obtained using SIMULINK for load voltage (RL load) and current is shown in Figs.10 and 11.
Fig. 10: Normalized FFT analysis of load voltage of MLI using hybrid modulation. Harmonic order vs. normalized magnitude (V).

Fundamental Component = 143.5 V
THD = 4.9%

Fig. 11: FFT spectrum of load current of MLI for hybrid modulation technique. Harmonic order vs. normalized magnitude (A).

Fundamental Component = 3.12 A
THD = 3.46%
4. Performance Parameters for MLI employing Hybrid modulation technique

The performance parameters considered for evaluating the proposed modulation strategy are: spectral quality of the output voltage, THD, DF$_1$, DF$_2$ and switching losses [10,11] which is discussed in this section. The results show that hybrid modulation technique gives a better performance for the MLI compared to the conventional PDPWM technique.

4.1 Total Harmonic Distortion (THD)

The total harmonic distortion is a measure of closeness in shape between a waveform and its fundamental component [12], the expression for THD is

\[
THD = \frac{1}{(V_o)_1} \sqrt{\sum_{3,5,7} \infty (V_o)^2_n}
\]  

(7)

Using equation (7), the theoretical value of THD is calculated for hybrid modulation strategy which is verified by simulation and experimental studies.

4.2 Distortion Factor (DF$_1$)

Inverter power supplies such as Uninterruptible Power Supplies (UPS) employ an L-C filter between the inverter and the load. The main purpose of this filter is to provide harmonic attenuation, which is proportional to the square of the order (n) of the harmonic. DF$_1$ represents the first-order attenuation of the harmonics in the output voltage of the inverter and it can be computed as

\[
DF_1 = \frac{1}{(V_o)_1} \sqrt{\sum_{2,3} \infty \left( \frac{V_{o,n}}{n} \right)^2}
\]  

(8)

4.3 Distortion Factor (DF$_2$)

Second-order attenuation in the harmonic voltages is obtained using a second-order filter in the output of the MLI. Therefore, DF$_2$ is given by

\[
DF_2 = \frac{1}{(V_o)_1} \sqrt{\sum_{2,3} \infty \left( \frac{V_{o,n}}{n^2} \right)^2}
\]  

(9)

4.4 Switching Losses

Switching loss is the power dissipation during turn-on and turn-off switching transitions. In high frequency PWM, switching loss can be substantial and must be considered in the thermal design of the inverter. It is a
big drawback that results in a series of problems such as increasing the cost of the inverter and decreasing its efficiency in high voltage and high power applications. Higher the power being processed, the more severe the effect of the switching loss becomes. Switching loss analysis for MLI is a complex process due to the wide number of switching states of the inverter [13,14]. Moreover, this analysis becomes more difficult by using a hybrid modulation technique, because the semiconductor devices, their gating signals and the switching frequencies are different for the two H-bridges (Fig.1). The most accurate method of determining switching losses is to plot the current and voltage waveform in the controllable switch during the switching transition and multiply the waveform point by point to get an instantaneous power waveform [15, 16]. The area under the power curve is the switching energy at turn-on or turn-off. The simulation results for switching losses using the proposed hybrid modulation and conventional PDPWM is shown in Table 5.5.

<table>
<thead>
<tr>
<th>Device / modulation</th>
<th>Switching loss (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLI (proposed hybrid modulation)</td>
<td>4.64 mJ (total switching losses)</td>
</tr>
<tr>
<td>MLI (conventional PDPWM)</td>
<td>14.50 mJ (total Switching Loss)</td>
</tr>
</tbody>
</table>

From Table 3, it is observed that the hybrid modulation results in minimized switching losses and improves the performance of MLI compared to conventional PDPWM. Figures 12 and 13 shows the DF curves for various modulation indices.
From the analyzes for THD, DF1, DF2 and switching loss, it can be concluded that the MLI with the hybrid modulation gives better performance compared to the conventional PDPWM technique.

5. Experimental Results

A single-phase seven-level asymmetric cascaded multilevel inverter has been built using IGBT FGA25N120. The inverter was controlled using hybrid modulation with modulation index (ma = 0.90). The gating signals were generated using FPGA processor. The experimental output of bridge H1 is shown in Figure 14.
The experimental output voltage for bridge H$_2$ is shown in Figure 15.

![Figure 15 Experimental output voltage for bridge H$_2$](image)

The output voltages of bridge H$_1$ and H$_2$ are added and the cascaded output for resistive load is shown in Figure 16.

![Figure 16 Seven-level output voltage of HCMLI](image)
6. Conclusion

A novel modulation strategy has been discussed for MLI. The technique combines a fundamental frequency method and VFISPWM technique. This control technique is compared with the conventional PDPWM. A comparative evaluation between hybrid modulation strategy and the conventional Phase Disposition (PD) PWM method has been presented in terms of output voltage quality, power circuitry complexity, Distortion Factor (DF) and THD. The performance of the asymmetric cascaded multilevel inverter employing hybrid modulation has been verified experimentally. From the results, it is concluded that the hybrid modulation method gives a better performance lower switching losses and THD for a chosen modulation index compared to the conventional PDPWM.

Reference


Biography

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 Shannughwa College of Engineering, Thanjavur in 1998 and Ph.D from Anna University, Chennai. She has been working in the teaching field for about 13 Years. She has published several papers in International Journals and International Conferences in the area of Power Electronics & Drives. Her areas of interest include SiC Power Devices, Multilevel Inverters, Modeling of fuel cells, Design of Interleaved Boost Converter, Multiport DC-DC Converter and control techniques for DC-DC Converter.