THD Analysis and Comparison of Different Cascaded Multilevel Inverters for Improving the Quality of Energy

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Abstract
Quality of energy is the main issue in all electrical supply due to various power quality problems. This problem is more dominant in ac supply system having power converter. Multilevel inverter can solve this problem by reducing harmonics in the supply system. This paper mainly aims to extend the knowledge about the different multilevel inverter topologies with THD analysis for different type of loads. These inverters can be useful for high power and medium voltage system. The modulation technique used is sinusoidal pulse width modulation technique for synthesizing wave forms with better harmonic spectrum and with less total harmonic distortion for generating a staircase waveform. This waveform is similar characteristics with sinusoidal waveform. The simulation for different multilevel inverter are done using MATLAB/SIMULINK.

Keywords: Quality of energy, Power Quality, Phase shifted, Level Shifted, THD, Filter

I. INTRODUCTION
Two-level inverter cannot operate smoothly at higher frequencies due to higher switching losses. Two-level inverter has the limitation of device rating. So higher level inverter known as multilevel inverter has been developed to solve the above drawbacks. The major benefit using multilevel inverter (MLI) as compared to two-level inverter are: smaller common mode voltage, stair case waveform quality due to which THD and \( \frac{dv}{dt} \) are lowered, draw input current with lesser distortion [1]-[5],[22].

II. TYPES OF MULTILEVEL INVERTERS
The multilevel inverters generate approx voltage of sinusoidal nature. It can be obtained from different voltage levels. By increasing levels, harmonic distortion at the output waveforms goes on decreases [6]-[9]. The three major divisions of multilevel inverters can be represented as:

1. Diode-clamped type multilevel(DCM) or Neutral point type clamped(NPC) multilevel
2. Flying-capacitor type multilevel(FCM) or Capacitor clamped multilevel(CCM)
3. Cascaded H-bridge type multilevel(CHM)

A. Advantages of using CHM inverter:
1. No use of clamping diodes as compared with DCM
2. No voltage balancing capacitors present as in FCM
3. Requires low voltage switching device
4. Generation of greater number output levels as comparing with the separate dc voltage sources used
5. During the damage of one of its cell, it has the capability to operate smoothly at reduced power level
6. No transformer required as in case of multi-pulse inverter
7. Voltage balancing circuits are not required due to Separate dc sources

One primary drawback is that, it needs separate sources of dc voltages. It increases as the level increases[10]-[14].

Fig-1: Single-phase multilevel Cascaded Inverter
III. MODULATION TECHNIQUE

Pulse width modulation (PWM) can be regarded as an efficient modulation technique. Because in PWM, additional components are not needed and it has the capability to reduce the harmonics and only higher order of harmonics are present. These higher orders of harmonics can be filtered smoothly by connecting filter circuits at the load terminal [15]-[17].

A. Multicarrier PWM Technique

The multicarrier based PWM technique can be classified as:

1. Phase shifted type modulation (PSM)
2. Level shifted type modulation (LSM)

There will be need of (n-1) high frequency range triangular waves for the inverter of n-level having equal peak to peak amplitude and frequency. These are needed for both the modulation [18]-[21]. Here n is the number of levels.

a) PSM

Between adjacent carrier waves, phase displacement of \( \phi_{cr} \) is given by

\[
\phi_{cr} = \frac{360}{n-1}\]

Where \( \phi_{cr} \) = phase angle between the adjacent triangular carrier waves, n represents the number of total output level of voltage.

b) LSM

There is vertical displacement of triangular waves in case of LSM. Based upon carrier waves disposition, LSM can be subdivided into three types. These are: phase opposition type disposition PWM (POD-PWM), alternate phase opposition type disposition PWM (APOD-PWM) and in phase type disposition PWM (IPD-PWM) [23]-[24].

1. In case of POD-PWM, it is observed that, there is presence of waves of carrier signals both the upper and lower region of values of zeros reference having a phase shift of 180\(^\circ\).
2. There is alternate displacement of 180\(^\circ\) of carrier waves in APOD-PWM.
3. In case of IPD-PWM, there is the presence of carrier wave signals (triangular) in a single phase.

IV. SIMULATION RESULTS

The simulation of various level of inverter (3-level, 5-level and 7-level) are performed using MATLAB. The input DC sources for all the individual bridges which are connected in cascaded are equal. This paper presents the comparison of output voltage and currents for different multilevel inverters for different loads. The harmonic spectrum can be compared for different loads with filter and without filter.

A. Analyzing different multilevel inverters with R-Load and without filter

By using R load, both the output phase voltage and current will be present in same phase. So the percentage of THD will be same for both voltage and current with or without filter.

1) PSM

In PSM technique, each high frequency carrier triangular signal will be phase displaced by an angle which is given by \( \frac{360}{n-1} \), where n= number of levels. Consider a case of five level inverter, where, n-1= total number of carrier signals. Here, n=5, so n-1=4. Hence four triangular waves will be phase displaced by 90\(^\circ\). Every individual bridge inverter generates desired gate signal by comparing four triangular signals with a sinusoidal reference signal.

i. Three Level Inverter

In three-level inverter each triangular signal will phase displaced by 180\(^\circ\) [22]. For generating desired firing pulses, sinusoidal signal are compared with triangular signals.

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Fig-2: Comparison of two carrier signals with a reference signal

Fig-3: Phase voltage output (3-level)

Fig-4: Output phase current (3-level)
ii. **Five level Inverter**

It has been observed that for a phase shifted multi-carrier three-level inverter, THD = 56.13%. It can be again minimized by using filter.

*nineteen level Inverter*

In nineteen-level inverter, six triangular carrier signals are required, which are phase shifted by 60°. For generating firing pulses, these triangular signals are juxtaposed with a signal of reference wave of sinusoidal waveform.

iii. **Seven level Inverter**

In seven-level inverter, six triangular carrier signals are required, which are phase shifted by 60°. For generating firing pulses, these triangular signals are juxtaposed with a signal of reference wave of sinusoidal waveform.
From the above waveform, it is observed that, the percentage of THD of 7-level inverter is found to be 20.22.

2) **LSM**

a. **APOD**

1) **Three Level Inverter**

Here, two carrier waves will be phase displaced by 180° from each other alternately. Fig. 13 represents the firing pulse generation of inverter by comparing two triangular waves which has the magnitude of same peak to peak value and their frequency is same but has out of phase of 180° with a reference of sinusoidal waveform.

![Fig-13: Output voltage’s FFT analysis (7-level)](image)

In APOD technique of modulation, the % of THD = 57.91%.

2) **Five Level Inverter**

In this technique of modulation, four signals(triangular waves) are 180° out of phase alternately will be compared with a sinusoidal signal.

![Fig-16: Firing pulse generation (5-level) inverter](image)

Here the THD value is obtained as 31.42%.

3) **Seven-level Inverter**

In seven-level APOD multicarrier modulation technique, for generating desired pulses, a sinusoidal reference signal is compared with six triangular carrier waves. Each triangular wave is phase displaced by 180° alternately.

![Fig-18: Firing pulse generation(7-level)](image)
For this seven level inverter, THD value is 19.64%.

b. In Phase Disposition

1. Three level Inverter

Here two triangular waves are in phase but displaced vertically with each other. For generating desired firing pulses of the inverter bridges, these triangular signals are compared with a sinusoidal signal.

The THD value is given as 54.57%.

2. Five Level Inverter

For generating the firing pulses, four triangular waves having in phase and vertically displaced and compared with a sinusoidal waveform.

3. Seven Level Inverter

In this modulation topology, carrier signal of six triangular are compared with a signal of sinusoidal waveform. Each triangular signal will be in phase with each other and vertically displaced. The peak to peak amplitude and frequency are same for all carrier signals.
THD value is given as 17.33%. As the level increases the THD value goes on decreasing. It is found that IPD gives better THD value as compare to other modulation technique.

c. Phase Opposition Disposition

1. Three Level Inverter

The THD value is given as 55.61%

2. Five Level Inverter

The THD value is given as 30.43%.

3. Seven Level Inverter

The THD value is given as 17.98%.

A. THD at various levels for different multilevel inverter with R-Load and without using filter

<table>
<thead>
<tr>
<th>Phase Voltage Levels</th>
<th>APOD</th>
<th>POD</th>
<th>IPD</th>
<th>Phase Shifted (PS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Level</td>
<td>58.34%</td>
<td>56%</td>
<td>54.55%</td>
<td>56.13%</td>
</tr>
<tr>
<td>5 Level</td>
<td>31.42%</td>
<td>30.63%</td>
<td>28.77%</td>
<td>30.1%</td>
</tr>
<tr>
<td>7 Level</td>
<td>19.78%</td>
<td>18.13%</td>
<td>17.49%</td>
<td>20.23%</td>
</tr>
</tbody>
</table>

B. THD at various levels with R-Load and with the use of filter

<table>
<thead>
<tr>
<th>Phase Voltage</th>
<th>APOD</th>
<th>POD</th>
<th>IPD</th>
<th>Phase Shifted (PS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Level</td>
<td>2.512%</td>
<td>2.36%</td>
<td>2.28%</td>
<td>2.393%</td>
</tr>
<tr>
<td>5 Level</td>
<td>1.383%</td>
<td>1.35%</td>
<td>1.35%</td>
<td>0.78%</td>
</tr>
<tr>
<td>7 Level</td>
<td>0.97%</td>
<td>1%</td>
<td>1.32%</td>
<td>0.53%</td>
</tr>
</tbody>
</table>

If a split phase induction motor is connected in place of R load then the harmonic quantity in output current will be changed where as THD value in output voltage waveform will be same as in case of R load.
C. %THD with Split Phase Induction Motor as Load and without using Filter

<table>
<thead>
<tr>
<th>Output Current</th>
<th>APOD</th>
<th>POD</th>
<th>IPD</th>
<th>Phase Shifting (PS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Level</td>
<td>5.37%</td>
<td>5%</td>
<td>4.86%</td>
<td>5%</td>
</tr>
<tr>
<td>5 Level</td>
<td>3%</td>
<td>2.93%</td>
<td>2.92%</td>
<td>1.73%</td>
</tr>
<tr>
<td>7 Level</td>
<td>2.1%</td>
<td>2.12%</td>
<td>2.54%</td>
<td>1.17%</td>
</tr>
</tbody>
</table>

D. Output Current Waveform of Split Phase Induction Motor

Fig-32: Output current of seven level IPD Inverter

V. CONCLUSIONS

Various multilevel inverters are modeled and analyzed for studying of their THD with the help of MATLAB/SIMULINK. It has been observed that, THD will be reduced gradually by increasing the levels of multilevel inverter. The harmonic spectrum can be further be minimized by the use of filter circuit. It has been seen that by simulating the multicarrier modulation of different level shifted topology and modulation topology of phase shifted multicarrier signals, the IPD modulation gives lesser THD and better output phase voltage waveform.

REFERENCES


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