SOME INVESTIGATION IN UNIPOLAR MODULATION TECHNIQUE TO NESTED NEUTRAL POINT CLAMPED (NNPC) CONVERTER

Akshaya D. Bonde, P. M. Meshram

Department of Electrical Engineering
Yeshwantrao Chavan College of Engineering (YCCE), Nagpur, India
{adbonde11@gmail.com, praful_1087@rediffmail.com}

Abstract

The multilevel inverters have become an effective and practical solution for increasing power and reducing harmonics of AC waveforms. Among various modulation techniques for a multilevel inverter, the sinusoidal pulse width modulation (SPWM) is widely used. This paper presents the unipolar modulation of Sinusoidal PWM with carrier signal PD, APOD, phase shifted, variable frequency and Third Harmonic Injected PWM, reference signal UISCPD-PWM, UISCAPOD-PWM and UISCVF-PWM strategy with sine and stepped wave reference. Unipolar scheme has the advantage of effectively doubling the switching frequency as far as the output harmonics are concerned, where the lowest harmonics appears as side bands of twice switching frequency. This different modulation techniques are applied to the newly introduced 5-level Nested Neutral Point Clamped Converter To illustrate the effectiveness of above modulation techniques, FFT analysis of output phase voltage of NNPC converter is investigated. The simulation of five-level NNPC converter has been carried out in MATLAB/SIMULINK software.

Key Words: multi-level inverter (MLI), pulse width modulation (PWM); nested neutral point clamped (NNPC) converter; total harmonic distortion (THD).

1. Introduction

In recent years there has been a growing interest in Voltage Source Multilevel Inverter (MLI) due to their numerous advantages. The technology of multilevel converters is very attractive for medium to high voltage range (2-13kV) applications, which includes motor drive systems, power distribution, power quality and power conditioning applications [1]. The advantages of the multilevel inverters compared to conventional two-level inverters are: higher voltage capability, reduction of input and output harmonic content, lower switching losses, higher amplitude fundamental and lower dv/dt [2]. However, the main disadvantages of multilevel inverters include voltage unbalance difficulties, unequal current stresses, and higher implementation cost. The most common topology groups of voltage source multilevel inverters are the following: the Diode-Clamped or Neutral Point Clamped Multilevel Inverter (NPC-MLI), the Flying Capacitor Multilevel Inverter (FC-MLI) and the Cascaded Cell Multilevel Inverter (CC-MLI) [3].

A recently introduced topology eliminates some drawbacks of simple neutral point clamped as well as FC converters. Basically, NNPC is the combination of NPC and FC converters; and is termed as Nested Neutral Point Clamped (NNPC) converter [5]. In this topology, connecting the array of power-semiconducting devices is not necessary for its operation in the range from 2.5 to 7.3KV. Comparing the two converters (NPC and FC) with NNPC topology, less number of components is required in case of NNPC converters. Presently, for this topology, even as odd level converters such as four [6], five [7] and seven-level [8] NNPC converters are introduced.

Pulse width modulation is a technique that generates variable width pulses to represent the amplitude of an analog input signal. It is required that inverter is to be made ON at high switching frequency. PWM basically offers a high switching frequency, so they are generally used to make inverters ON. Also by using PWM the harmonics are reduced thus making the input signal smooth. Power loss in switching devices is reduced to very low value. In this method, a fixed dc input voltage is given to the inverter and a controlled ac output voltage is obtained by adjusting the on and off periods of the inverter components.

The various pulse width modulation techniques are Sinusoidal Pulse Width Modulation (SPWM)[9], Space Vector Pulse Width Modulation (SVPWM) [10], Trapezoidal Pulse Width Modulation (TPWM), Selective Harmonic Elimination( SHE) [11] and etc. The SPWM, SVPWM and Selective Harmonic Elimination techniques are applied to voltage source inverters (VSI) whereas Trapezoidal PWM is applied to current source inverters (CSI). An inverter produces an AC output voltage from a DC input by using switching circuits to simulate a sine wave by producing one or more square pulses of voltage per half cycle. If the widths of the pulses...
are adjusted as a means of regulating the output voltage, the output is said to be pulse width modulated [12]-[13].

The two different strategies in SPWM are unipolar and bipolar SPWM. The number of output voltage pulses and the frequency of the lowest harmonic voltage in unipolar SPWM are twice that of bipolar SPWM with the same switching frequency, so the Unipolar SPWM facilitates the choice of filter and has better output waveforms [14]. So far, the Unipolar PWM technique is not yet applied to this NNPC converter topology. This paper presents some investigation in Unipolar Modulation Technique to Nested Neutral Point Clamped (NNPC) Converter. Some of the Unipolar modulation techniques [15] are applied to NNPC converter and its performance is checked by observing its spectral analysis for various carrier disposition PWM methods.

This paper is arranged as: the operation of 5-level NNPC converter is covered in section II. The Unipolar PWM techniques are explained in section III. Fourth section shows the application of above considered modulation technique to the NNPC converter followed by the Simulation results in next section. Finally, section-VI concludes the paper.

2. Five-level Nnpc Converter

Nested Neutral Point Clamped inverter basically combines advantages of flying capacitor as well as neutral point clamped converter. The five-level NNPC converter is presented in Fig.1. Each phase of converter has eight switching devices, two clamping diodes, & three flying capacitors. Output voltage of each phase is limited to the five voltage levels ($\pm V_{dc}/2$, $\pm V_{dc}/4$, 0). Table I shows the switching combinations of 5-level NNPC converter [5].

Apart from this listed switching states, inverter is having 3 more switching combinations to get $\pm V_{dc}/4$ and 4 switching events for zero voltage level. These redundant states are advantageous to attain the voltage stabilizing of capacitors. Capacitor $C_{x}$ is charged to three-fourth of dc bus voltage ($3V_{dc}/4$) and $C_{y}$ & $C_{z}$ are charged to one fourth of dc bus voltage ($V_{dc}/4$) in order to generate five output levels and ensure that the power switches share the same voltage stress [5]; x represents the phases a, b and c. Converter working operation is described in the Fig. 2. Dark lines show conducting paths when the switches are conducting.

![Fig. 1: 3-phase 5-level NNPC (Nested Neutral Point Clamped) converter [5]](image)

![Table 1: Five-level Switching Combinations of NNPC Inverter](image)

| Output Voltage Level | Switching States ($x=a, b, c$) |
|----------------------|--------------------------------|
| $+V_{dc}/2$          | $S_{x1}$ $S_{x2}$ $S_{x3}$ $S_{x4}$ $S_{x5}$ $S_{x6}$ $S_{x7}$ $S_{x8}$ |
| $+V_{dc}/4$          | 1     1     0     1     1     0     0     0 |
| 0                    | 1     1     0     0     1     1     0     0 |
| $-V_{dc}/4$          | 0     0     0     1     1     0     1     1 |
| $-V_{dc}/2$          | 0     0     0     1     1     1     1     1 |

![Fig. 2: Working of Five-level NNPC converter](image)

(Dark lines show the Conduction of switches)

3. Unipolar Modulation Scheme

The two different strategies in SPWM are unipolar and bipolar SPWM. The number of output voltage pulses and the frequency of the lowest harmonic voltage in unipolar SPWM are twice that of bipolar SPWM with the same switching frequency, so the Unipolar SPWM facilitates the choice of filter and has better output waveforms.

This paper presents five types of unipolar PWM strategies and three types of unipolar inverted sine carrier (UISC) strategies. The reference in the unipolar strategy may be a rectified sinusoidal waveform or two sine references (sine and 180° phase shifted Sine wave) the later is used for inverter switching. The multi carriers are positioned above zero level. For an m-level inverter using unipolar multi-carrier technique, (m-1)/2 carriers with the same frequency fc and same peak-to-peak amplitude Ac are
used. The reference waveform has amplitude $A_m$ and frequency $f_m$ and it is placed at the zero reference. The reference wave is continuously compared with each of the carrier signals. If the reference wave is more than a carrier signal, then the active devices corresponding to that carrier are switched on. Otherwise, the device switches off. The frequency ratio $m_f$ is defined in the unipolar PWM strategy as follows:

$$m_f = \frac{f_c}{f_m}$$  \hspace{1cm} (1)

In this paper, $m_f = 30$ and $m_a$ is varied from 0.8 to 1.

The modulation techniques can be generally classified into the following three categories: multi-step or staircase modulation techniques, carrier-based PWM techniques and space vector PWM techniques. The general principle of a carrier-based PWM technique is the comparison of a sinusoidal waveform with a carrier waveform, this typically being a triangular waveform. The carrier frequency defines the switching frequency of the converter and the high order harmonic components of the output voltage. The unipolar modulation scheme can also be implemented by using only one modulating wave but in that case two phase shifted carrier waves are of same amplitude and frequency, but 180 degrees out of phase from each other. Moreover, the carrier frequency is found as a component of the output voltage spectrum and sidebands occur around the carrier frequency and its multiples.

For multilevel applications, carrier-based PWM techniques with multiple carriers are used. The unipolar multicarrier techniques can be applied in many alternative ways, some of them are tried in this paper and they are:

(i) Unipolar Phase disposition PWM (UPD-PWM), where all carriers are in phase.

(ii) Unipolar Alternative phase opposition disposition PWM (UAPOD-PWM), where each triangular carrier is phase shifted by 180° form its adjacent carrier,

(iii) Unipolar Phase Shifted PWM (UPS-PWM) is the standard modulation strategy.

(iv) Unipolar Variable Frequency PWM (UVF-PWM), where the carrier signals are of different frequencies but same peak-to-peak amplitude.

(v) Unipolar Third Harmonic Elimination PWM (UTHI-PWM), where third harmonic component is added to the fundamental signal.

A. Unipolar Phase Disposition PWM (UPD-PWM):

In Phase Disposition (PD), all the carrier waves are in same phase. The carrier arrangement of this technique is illustrated in Fig. (3). In comparison with POD, APOD pulse width modulations; IPD provides better harmonic profile so it is preferred mostly.

![Fig. 3 : Unipolar Phase Disposition PWM Strategy (UPD-PWM)](image)

ma for unipolar phase disposition PWM strategy is given by:

$$m_a = \frac{2A_m}{(m-1)A_c}$$  \hspace{1cm} (2)

B. Unipolar Alternative Phase Opposition Disposition PWM (UAPOD-PWM):

In unipolar Alternate Phase Opposition Disposition (UAPOD) strategy, the carriers of same amplitude are phase displaced from each other by 180 degrees alternately. The carrier arrangement of this strategy is as shown in Fig. (4). With this method, the most significant harmonics are centered aside bands around the carrier and the amplitude modulation index $m_a$ for UAPOD is same as given in Eqn. (2).

![Fig. 4 : Unipolar Alternative Phase Opposition Disposition PWM Strategy (UAPOD-PWM)](image)

C. Unipolar Phase Shifted PWM (UPS-PWM):

In this method, similar to bipolar sinusoidal reference PS-PWM, the carriers are phase shifted but all the carriers are arranged above the zero level.

![Fig. 5 : Unipolar Phase Shifted PWM Strategy (UPS-PWM)](image)
The amplitude modulation index is defined for this strategy as follows:

\[ m_a = \frac{A_m}{A_c} \]  

(3)

All the triangular carriers have the same frequency and same peak-to-peak amplitude, but there is a phase shift between any two adjacent carrier waves, given by:

\[ \theta_{ph} = \frac{2\pi}{(m-1)} \]  

(4)

where, \( m \) is the no. of voltage level by each leg. Phase-shifted modulation is based on the harmonic analysis of PWM signals. It is possible to set phase shift in order to obtain output voltage free of some harmonics that existed in single inverter cases.

**D. Unipolar Variable Frequency PWM (UVF-PWM)**

The number of switching for upper and lower devices of chosen MLI is much more than that of intermediate switches in SHPWM using constant frequency carriers. In order to equalize the number of switching for all the switches, variable frequency PWM strategy is used as illustrated in Fig. 6.

![Fig. 6: Unipolar Variable Frequency PWM Strategy (UVF-PWM)](image)

**E. Unipolar Third Harmonic Elimination PWM (UTHI-PWM)**

Inverter phase voltage can be increased by adding third harmonic component to the three phase sinusoidal modulating wave. This modulation technique is known as third harmonic injection PWM.

![Fig. 7: Third Harmonic Injection (THI)](image)

Fig. 7 describes the principle of third harmonic injection PWM scheme where the modulating wave is obtained by adding third harmonic to the fundamental wave. The resulting flat-topped waveform allows over-modulation (with respect to the original SPWM technique) while maintaining excellent ac term and dc term spectra.

The obtained waveform and 180° phase shifted ones are super imposed in case of unipolar THI-PWM as shown in Fig. 8.

![Fig. 8: Unipolar Third Harmonic Elimination PWM Strategy (UTHI-PWM)](image)

**F. Unipolar Inverted Sine Carrier Phase Disposition PWM (UISCPD-PWM)**

The principle of the UISCPD-PWM strategy is to use several triangular carriers with two modulation waves. For five-level inverter, two triangular carriers of the same frequency \( f_c \) and the same peak-to-peak amplitude \( A_c \) are disposed. The carrier set is placed above the zero reference. Carrier arrangements for five level UISCPD PWM are shown in Fig. 9. The modulation index is given by:

\[ m_a = \frac{A_m}{(n \cdot A_c)} \]  

(5)

where, \( n \) is the number of carriers.

![Fig. 9: Unipolar Inverted Sine Carrier Phase Disposition PWM Strategy (UISCPD-PWM)](image)

**A. Unipolar Inverted Sine Carrier Alternative Phase Opposition Disposition PWM (UISCAPOD-PWM):**

Carriers are having same amplitudes but are phase displaced in such a manner that each carrier is out of phase with its neighbouring carrier by 180 degrees alternatively as shown in arrangement in Fig. (10)
H. **Unipolar Inverted Sine Carrier Variable Frequency PWM (UISCVF-PWM):**

The number of switching for upper and lower devices of chosen MLI is much more than that of intermediate switches in PDPWM using constant frequency carriers. In order to equalize the number of switching for all the switches, variable frequency PWM strategy is used as illustrated in Fig. 10. The modulation index is same as that of UISCPD-PWM.

4. **Simulation Results**

Simulations are performed for all the above mentioned strategies for three different values of \( m_a \) (0.8, 0.9, 1) and the corresponding % THDs of the five-level NNPC Converter output phase voltages are observed using spectral analysis and their values are shown in Table 2. The output phase voltages of NNPC converter and their corresponding FFT analysis, for different unipolar modulation schemes are shown for only one sample value of \( m_a = 0.9 \).
Table 2: Comparison Table Of Different Unipolar Modulation Techniques

| Modulation Index | Fundamental Phase Voltage | % THD   |
|------------------|---------------------------|---------|
|                  |                           |         |
| A. Using UPD-PWM Strategy: |                     |         |
| 0.8              | 2386 V                    | 32.57%  |
| 0.9              | 2867 V                    | 29.48%  |
| 1.0              | 3032 V                    | 25.36%  |
| B. Using UAPOD-PWM Strategy: |                     |         |
| 0.8              | 2365 V                    | 35.75%  |
| 0.9              | 2827 V                    | 30.39%  |
| 1.0              | 3012 V                    | 25.63%  |
| C. Using UPS-PWM Strategy: |                     |         |
| 0.8              | 2612 V                    | 40.13%  |
| 0.9              | 2834 V                    | 35.55%  |
| 1.0              | 3020 V                    | 30.78%  |
| D. Using UVF-PWM Strategy: |                     |         |
| 0.8              | 2397 V                    | 37.82%  |
| 0.9              | 2846 V                    | 30.43%  |
| 1.0              | 3008 V                    | 26.02%  |
Simulation results for different strategies are presented. The unipolar sine carrier (UISC) SPWM methods are preferred mostly. Also comparing the unipolar inverted technique provides better harmonic profile and so it is compared with the unipolar SPWM methods, UPD-PWM without increasing the harmonics. As seen from Table II, reference enhances the fundamental by about 15 percent modulation range. So, any carriers employed for this fundamental voltage increases without entering the over decreases. In case of third harmonic injection method, the bipolar SPWM techniques. As modulation index number of carriers is reduced to half as compared to the complexity of the pulse generation is reduced as the technique improves the fundamental voltage. The phase five-level NNPC converter. The unipolar SPWM are investigated by applying these techniques to single In this paper, some of the unipolar modulation techniques are investigated by applying these techniques to single phase five-level NNPC converter. The unipolar SPWM technique improves the fundamental voltage. The complexity of the pulse generation is reduced as the number of carriers is reduced to half as compared to the bipolar SPWM techniques. As modulation index increases fundamental output voltage increases and THD decreases. In case of third harmonic injection method, the fundamental voltage increases without entering the over modulation range. So, any carriers employed for this reference enhances the fundamental by about 15 percent without increasing the harmonics. As seen from Table II, comparing the unipolar SPWM methods, UPD-PWM technique provides better harmonic profile and so it is preferred mostly. Also comparing the unipolar inverted sine carrier (UISC) SPWM methods, UISCPD-PWM technique provides better harmonic profile. The simulation results for different strategies are presented.

### E. Using UTHI-PWM Strategy:

| Modulation Index | Fundamental Phase Voltage | % THD |
|------------------|---------------------------|-------|
| 0.8              | 2994 V                    | 38.16%|
| 0.9              | 3274 V                    | 43.15%|
| 1.0              | 3374 V                    | 45.03%|

### F. Using UISCPD-PWM Strategy:

| Modulation Index | Fundamental Phase Voltage | % THD |
|------------------|---------------------------|-------|
| 0.8              | 2742 V                    | 31.53%|
| 0.9              | 3055 V                    | 27.86%|
| 1.0              | 3301 V                    | 24.71%|

### G. Using UISCAPOD-PWM Strategy:

| Modulation Index | Fundamental Phase Voltage | % THD |
|------------------|---------------------------|-------|
| 0.8              | 2506 V                    | 32.82%|
| 0.9              | 2972 V                    | 29.65%|
| 1.0              | 3118 V                    | 25.29%|

### H. Using UISCVF-PWM Strategy:

| Modulation Index | Fundamental Phase Voltage | % THD |
|------------------|---------------------------|-------|
| 0.8              | 2734 V                    | 31.19%|
| 0.9              | 3071 V                    | 28.36%|
| 1.0              | 3058 V                    | 26.03%|

5. Conclusion

In this paper, some of the unipolar modulation techniques are investigated by applying these techniques to single phase five-level NNPC converter. The unipolar SPWM technique improves the fundamental voltage. The complexity of the pulse generation is reduced as the number of carriers is reduced to half as compared to the bipolar SPWM techniques. As modulation index increases fundamental output voltage increases and THD decreases. In case of third harmonic injection method, the fundamental voltage increases without entering the over modulation range. So, any carriers employed for this reference enhances the fundamental by about 15 percent without increasing the harmonics. As seen from Table II, comparing the unipolar SPWM methods, UPD-PWM technique provides better harmonic profile and so it is preferred mostly. Also comparing the unipolar inverted sine carrier (UISC) SPWM methods, UISCPD-PWM technique provides better harmonic profile. The simulation results for different strategies are presented.

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