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A Review on Modulation Strategies of Multi Level Inverter

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Abstract

This review develops different switching methods for Multi Level Inverter (MLI). The switching methods proposed in this paper are to compare various methods and to predict exact switching method for different application based upon its quality of the outputs. The performance of the inverter is analyzed with the parameters like THD (Total Harmonic Injection), V_{RMS} (fundamental), CF (Crest Factor), FF (Form Factor) and DF (Distortion Factor). From the various non PWM (Pulse Width Modulation) and PWM methods the analysis are method to identify the exact PWM strategies for specific applications.

Keywords: *flip flop, SHE, hybird, variable amplitude, PWM*

1. Introduction

The power electronic device which converts DC input voltage to AC output voltage at required voltage and frequency level is known as inverter. The AC output voltage could be of fixed or variable magnitude at fixed or variable frequency. For low and medium power outputs, transistorized inverters can be used and for high power outputs, IGBTs can be used as switching devices. The DC input voltage to the inverter may be from batteries, fuel cells, solar cells, photovoltaic arrays or other DC sources. But in most industrial applications, inverter is fed by a rectifier.

Inverters are mainly classified according to the nature of input source as voltage source and current source inverters. The inverters can also be classified according to the nature of output voltage waveform as square wave, quasi-square wave and PWM inverters. The PWM strategies involve either (i) single carrier or (ii) multi-carriers which can be (a) bipolar or unipolar (b) triangular or rectified sine along with references which can be single sinusoid or third harmonic injection or 60 degree PWM or stepped wave or trapezoidal amalgamated or triangular or discontinuous PWM. The inverters can be further classified based on method of connections as series inverters, parallel inverters and bridge inverters. Based on number of phases, the inverters can be grouped as single phase and three phase inverters.

The inverter gain is the ratio of the AC output voltage to DC input voltage (V_{dc}). The output voltage of inverter may not remain constant due to the disturbances in the input voltage or load of inverter. At the same time some special applications require variation of output voltage. Therefore output voltage of inverter has to be controlled to the desired level. The various methods for the control of output voltage of inverters are as follows:

1. External control of AC output voltage
2. External control of DC input voltage
3. Internal control of inverter

The first two methods require the use of peripheral components whereas the third method requires no peripheral components. The internal control of inverter is done by two methods. They are (i) series inverter control and (ii) PWM control.

2. Modulation Strategies

Multilevel inverter with PWM control is an effective solution for increasing power and reducing harmonics of AC waveforms. A multilevel inverter has many advantages over the

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conventional bipolar inverter: (i) the voltage stress on each switch is decreased due to series connection of the switches and therefore the rated voltage and consequently the total power of the inverter could be safely increased. (ii) the rate of change of voltage (dv/dt) is decreased due to the lower voltage swing of each switching cycle. (iii) total harmonic distortion is also reduced due to more output levels. (iv) lower acoustic noise and Electro Magnetic Interference (EMI) is obtained. The other main advantages of PWM inverters are (i) control over output voltage magnitude (ii) reduction in magnitudes of unwanted harmonic voltages and (iii) improved power factor with unity displacement factor. Lowest order harmonic elimination is possible by proper choice of the number of pulses per half cycle.

Although multilevel inverter offers several advantages, the control strategies of MLI are quite challenging due to the complexity to cater the transitions between the voltage levels (or steps). A number of modulation strategies are used in multilevel power conversion applications. The various PWM techniques usually employed in MLIs can be classified into following categories are as follows.

2.1. Non PWM Methods
2.1.1. Using Embedded Control (Codlings)
The switching states are given as the input by using the MATLAB/SIMULINK. The inputs are given in the form of Matlab coding.

2.1.2. Using Flip Flops
In this method the Boolean equations are given as the input for the each switch of the CMLI. The Boolean equations can be forming by using the flip flops and the logic gates. Each switch requires number of logic gates. By using the switching states the Boolean equations can be formed.

2.2. Selective Harmonic Elimination
SHE PWM technique uses many mathematical methods to eliminate specific harmonics such as 5th, 7th, 11th, and 13th harmonics. The popular Selective Harmonic Elimination method is also called fundamental switching frequency based on harmonic elimination Theory.

2.3. RPWM Method
The random pulse width modulation (RPWM) has become an established means for mitigation of undesirable side effects in PWM converters, the voltage source inverters in adjustable speed ac drives in particular. Significant improvement in the acoustic and electromagnetic noise in RPWM converters has been observed from the output.

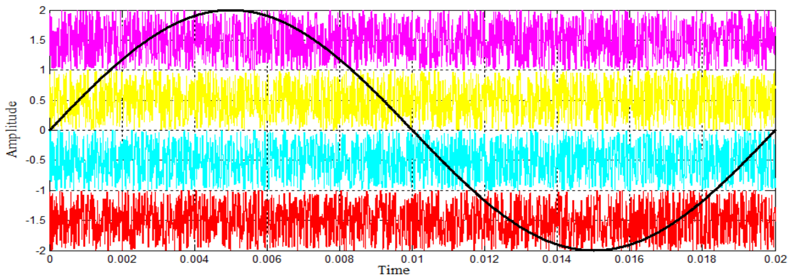

Figure 1. Sample Multi-Carrier Arrangement for RPWM

2.4. SPWM methods
Several CFDs (Control Freedom Degree) exist in multicarrier PWM strategies for MLIs. These strategies have more than one carrier option that can be triangular, inverted sine wave, saw tooth, a new function etc. As far as the particular carrier signals are concerned, there are multiple CFD including function, frequency, amplitude, phase of each carrier and offset between carriers.

2.4.1. Based on Reference and Carrier

a) SRMC (Single Reference Multiple Carrier)

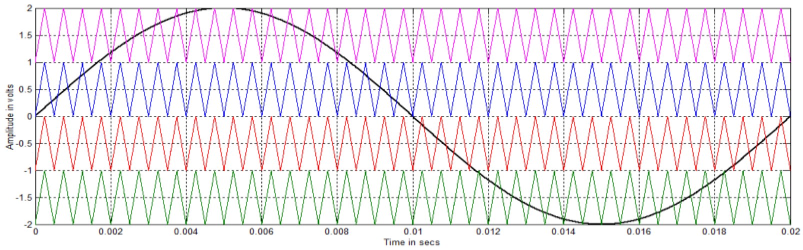

Figure 2. Sample multi-carrier arrangement for SRMC

b) SRSC (Single Reference Single Carrier)

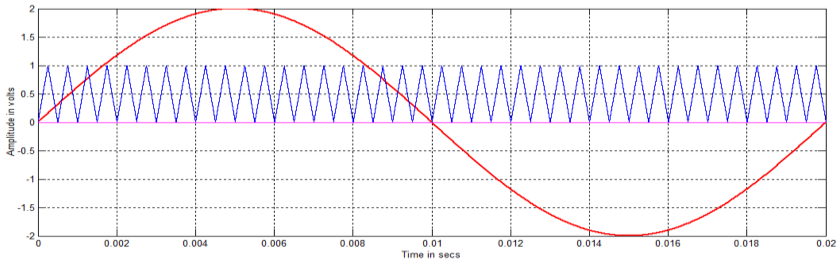

Figure 3. Sample multi-carrier arrangement for SRSC

c) MRMC (Multiple Reference Multiple carrier)

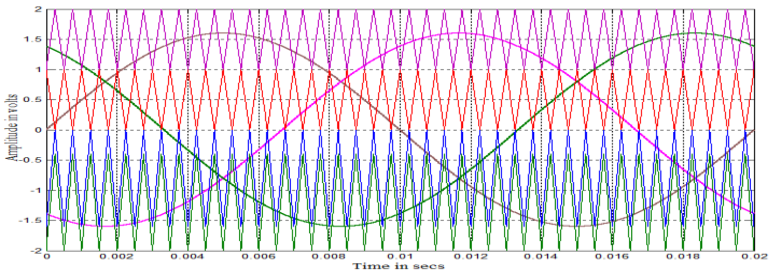

Figure 4. Sample multi-carrier arrangement for MRMC

d) MRSC (Multiple Reference Single Carrier)

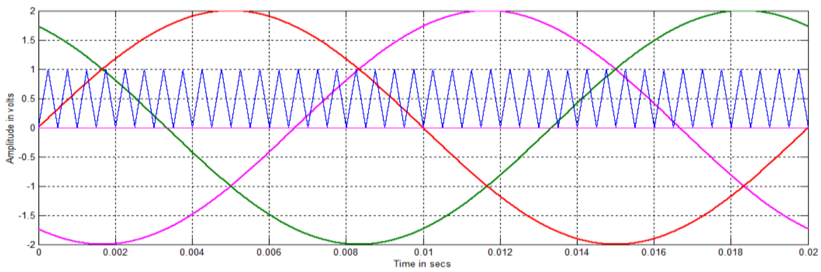

Figure 5. Sample multi-carrier arrangement for MRSC

2.4.2. Based on types of PWM strategies on carrier arrangement

a) PD (Phase Disposition)

In the present work, the multi-carrier based phase disposition PWM scheme is used. Figure 6 demonstrates the sine-triangle method for a five-level inverter where in modulation or sinusoidal reference signal is compared with four (m-1 in general) triangle waveform when the number of output voltage level is 5 (= m), 4 (m –1) carrier waveforms are arranged so that every carrier is in phase.

1) The carriers are in phase across all the bands. For this technique, significant harmonic energy is concentrated at the carrier frequency but since it is a co-phasal component, it doesn't appear in the line-to-line voltage.

2) The frequency modulation index $m_f = \frac{f_c}{f_m}$

3) The amplitude modulation index $m_a = \frac{2A_m}{A_c(m-1)}$

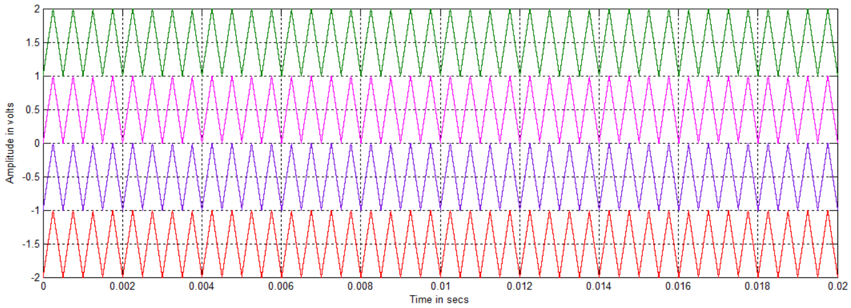

Figure 6. Sample multi-carrier arrangement for PDPWM strategy

b) POD (Phase Opposition and Disposition)

For POD modulation all carrier waveforms above zero reference are in phase and they are 180^0 out of phase with those below zero (Figure 2-5). When the number of level is m (= 5), m – 1 (= 4) carrier waveforms are arranged so that all carrier waveforms above zero are in phase and are 180^0 out of phase with those below zero. The significant harmonics are located around the carrier frequency for both the phase and line-to-line voltage. Formula for m_a and m_f are same as that of PDPWM technique.

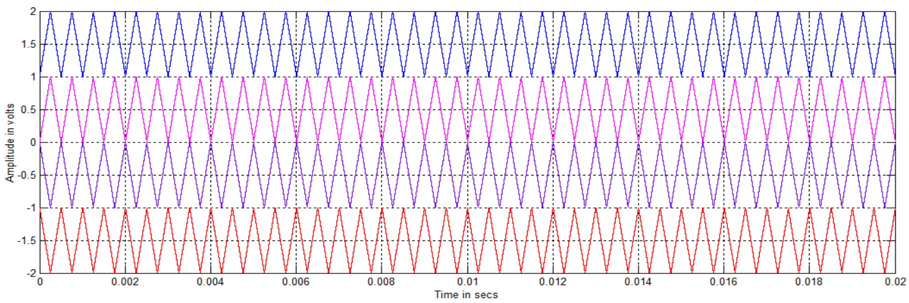

Figure 7. Sample multi-carrier arrangement for PODPWM strategy

c) APOD (Alternative Phase Opposition and Disposition)

In case of APOD modulation, every carrier wave is out of phase with its neighbour carrier by 180 degree. Since APOD and POD schemes in case of three level inverter are the same, a five level inverter is considered to discuss about the APOD scheme. When the number of level m (= 5) , m – 1 = 4 carrier waveforms are arranged so that every carrier waveform is in out of phase with its neighbor carrier by 180^0 (Figure 8) Carriers in adjacent bands are phase displaced by 180°. With this method, the most significant harmonics are centred as side bands around the carrier. Formula for m_a and m_f are same as that of PDPWM strategy.

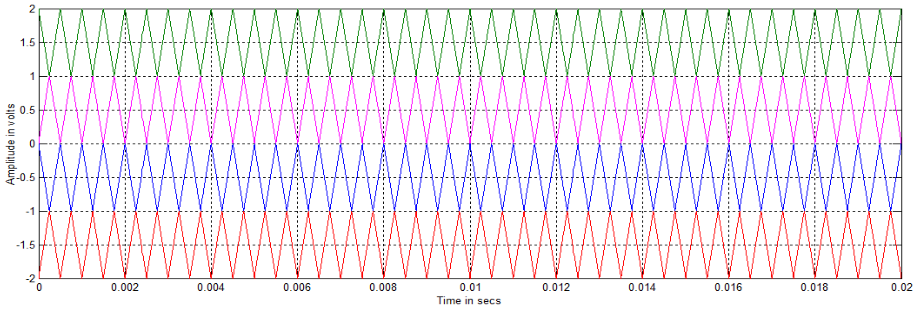

Figure 8. Sample multi-carrier arrangement for APODPWM strategy

d) COPWM (Carrier Overlapping)

The COPWM-A method utilizes the CFD of vertical offsets among carriers. The principle of COPWM-A is to use several overlapping carriers with single modulating signal. For an m level inverter, m-1 carriers with the same frequency f_c and same peak-to-peak amplitude A_c are disposed such that the bands they occupy overlap each other. The overlapping vertical distance between each carrier is $A_c/2$ in this work. The reference wave has the amplitude A_m and frequency f_m and it is centered in the middle of the carrier signal. Within this COPWM strategy, combination of varied vertical and/or horizontal offsets are adopted to get different species such as COPWM-A, COPWM-B and COPWM-C. The amplitude modulation index is:

$$m_a = \frac{A_m}{\left(\frac{m}{4}\right) * A_C}$$

Actually COPWM-A and COPWM-C can be looked on as a second control freedom degree change besides offset in vertical: the carriers have horizontal phase shift from COPWM-A.

1) COPWM - A

The vertical offset of carriers for chosen five level inverter can be illustrated in Figure 9. It can be seen that the four carriers are overlapped with other and the reference sine wave is placed at the middle of the four carriers.

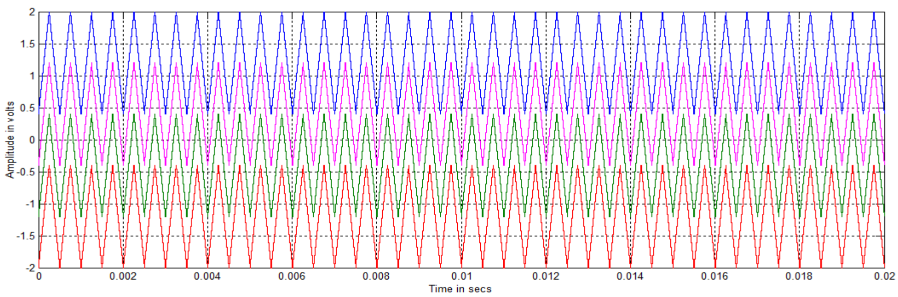

Figure 9. Sample Multi-Carrier Arrangement for COPWM-A strategy

2) COPWM - B

Carriers for chosen five level inverter with COPWM-B strategy are shown in Figure 10. It can be seen that they are divided equally into two groups according to the positive/negative average levels. In this strategy, the two groups are opposite in phase with each other while keeping in phase within the group.

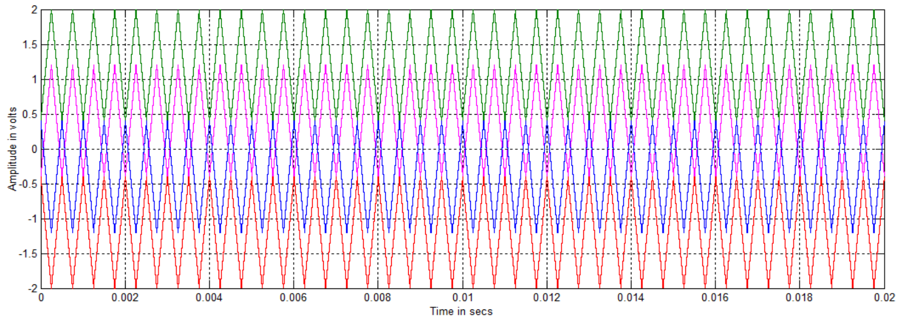

Figure 10. Sample multi-carrier arrangement for COPWM-B strategy

3) COPWM – C

Carriers for chosen five level inverter with COPWM-C strategy are shown in Figure 11. In this strategy, carriers invert their phase in turns from the previous one. It may be identified as PWM with amplitude overlapped and neighbouring phase interleaved carriers.

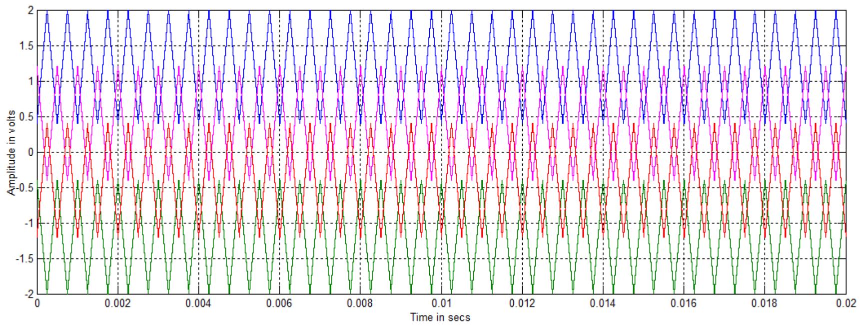

Figure 11. Sample multi-carrier arrangement for COPWM-C strategy

e) VF (Variable Frequency)

The number of switching for upper and lower devices of chosen DCMLI is much more than that of intermediate switches in above PWM strategies using constant frequency carriers. In order to equalize the number of switchings for all the switches, VFPWM strategy is used as illustrated in Figure 7 in which the carrier frequency of the intermediate switches is properly increased to balance the numbers of switching for all the switches. Figure 12 shows the multi-carrier arrangement for VFPWM technique for $m_a = 0.8$ and $m_f = 40$ for upper switches and $m_f = 80$ for intermediate switches. The amplitude modulation index for VFPWM strategy is:

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

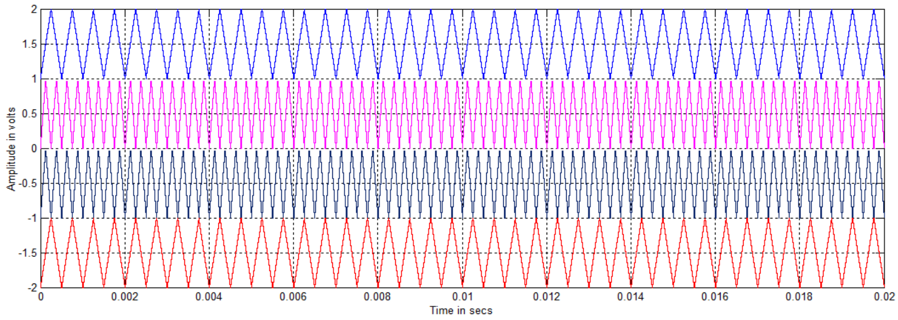

Figure 12. Sample multi-carrier arrangement for VFPWM strategy

f) PS (Phase Shift)

The phase shifted multicarrier PWM method uses four carrier signals of the same amplitude and frequency which are phase shifted by 90 degrees to one another to generate five level output. Figure 13 shows the phase shifted carriers and the reference wave for the chosen inverter.

A lower m_f is sufficient for this strategy to obtain the same number of sampling of carriers in other non phase shifted carrier strategies because of the inherent phase shift among the carriers in this strategy. f_c and hence m_f are to be appropriately chosen based on the number of carriers in this strategy.

The amplitude modulation index: $m_a = \dfrac{A_m}{\left(\dfrac{A_c}{2}\right)}$

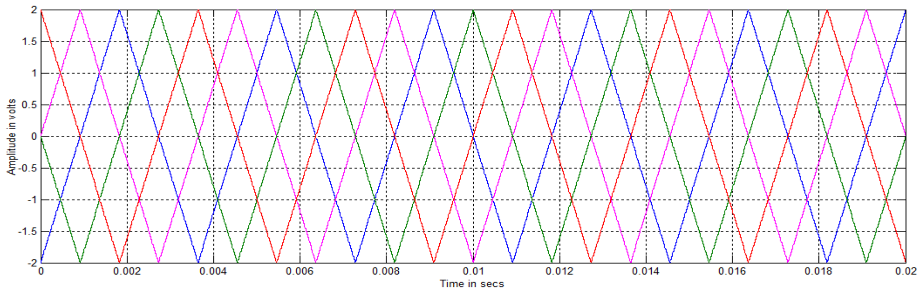

Figure 13. Sample multi-carrier arrangement for PSPWM strategy

2.4.3. Based on type of reference and carrier

1) **Bipolar Triangular Carrier**
2) **Bipolar Inverted Sine Carrier**

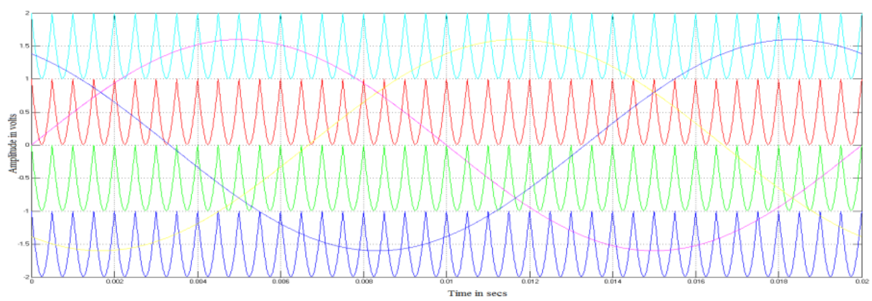

Figure 14. Sample multi-carrier arrangement for ISCPDPWM strategy

3) Bipolar Reference

The reference wave in the bipolar strategy may be a sinusoid or third harmonic injection or 60 degree PWM or stepped wave or trapezoidal amalgamated or discontinuous PWM. The multi-carriers (triangular or inverted sine) are positioned above and below zero level.

a) Sinusoidal Reference

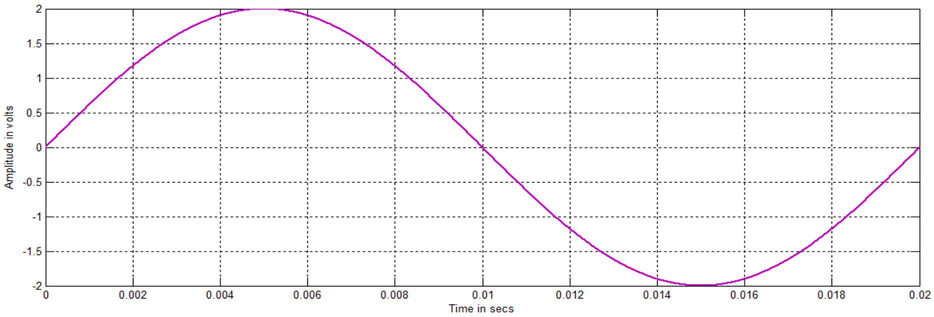

Figure 15. Sample sinusoidal reference signal

b) THIRD Harmonic Reference

The THI PWM reference is similar to the selected harmonic injection method and it is implemented in the same manner as sinusoidal PWM. The difference is that the reference wave is not sinusoidal but consists of both a fundamental component and a third harmonic component. As a result, the peak of reference wave is not sinusoidal but consists of both a fundamental component and a third harmonic component (Fig. 16). The peak to peak amplitude of the resulting reference function does not exceed the DC supply voltage V_{dc} but the fundamental component is higher than the available supply V_{dc}. The presence of exactly the same third harmonic component in each phase results in an effective cancellation of the third harmonic component in the neutral terminal. The peak line voltage is approximately 15.5% higher in amplitude than that achieved by the sinusoidal PWM. Therefore, the third harmonic PWM provides better utilization of the DC supply voltage than the sinusoidal PWM does. Harmonic elimination techniques which are suitable for fixed output voltage increase the order of harmonics and reduce the size of output filter.

The modulating signal is generally composed of:

$V_m = 1.15 \sin \omega t + 0.27 \sin 3 \omega t – 0.029 \sin 9 \omega t$

If only third harmonic is injected, V_m is given by:

$V_m = 1.15 \sin \omega t + 0.19 \sin 3\omega t$

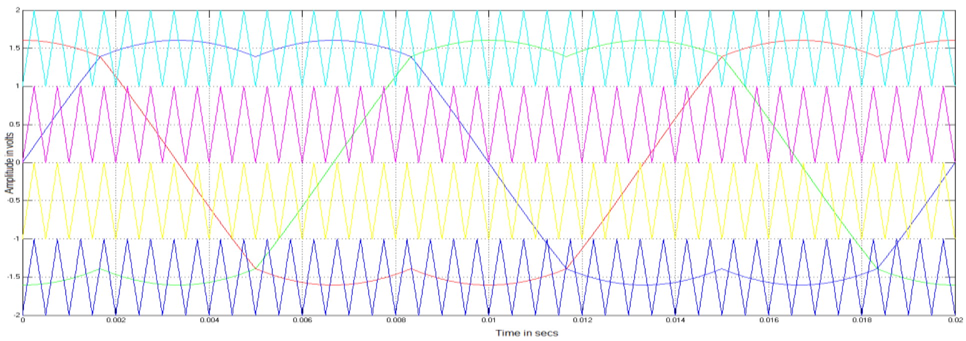

Figure 16. Sample THI reference signal

c) 60 degree Reference

This method is almost similar to sinusoidal PWM except that the modulating sine wave is flat topped for a period of 60 degree in each half cycle. 60 degree PWM reference technique is as shown in Figure 17.

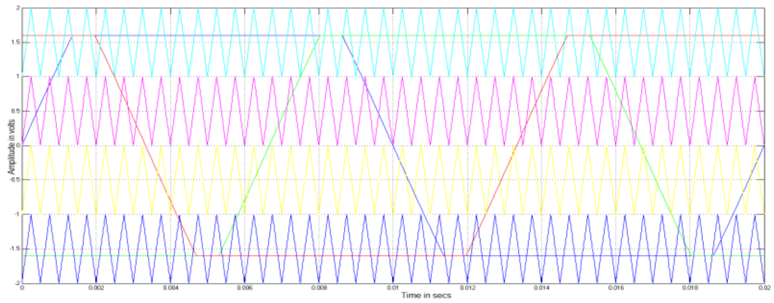

Figure 17. Sample 60 Degree Reference Signal

d) Stepped Wave Reference

The stepped wave is a sampled approximation to the sine wave. It is divided into specified intervals (say 20^0) with each interval controlled individually to control magnitude of the fundamental component and to eliminate specific harmonics. This type of control gives low distortion but higher fundamental amplitude compared with that of normal PWM control. Stepped wave reference based PDPWM technique is shown in Figure 18.

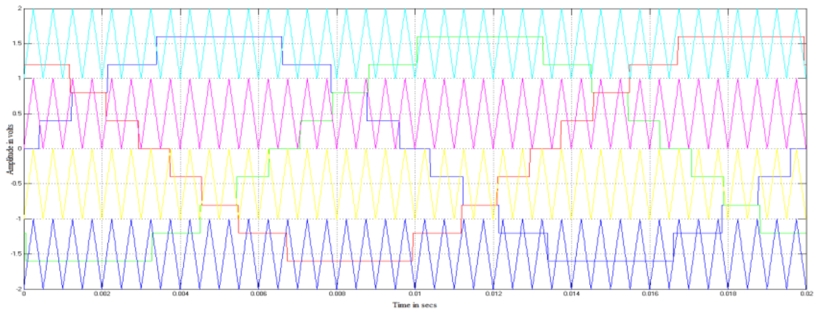

Figure 18. Sample Stepped Wave Reference Signal

e)Triangular Reference

In these methods instead of sine reference triangular reference is used.

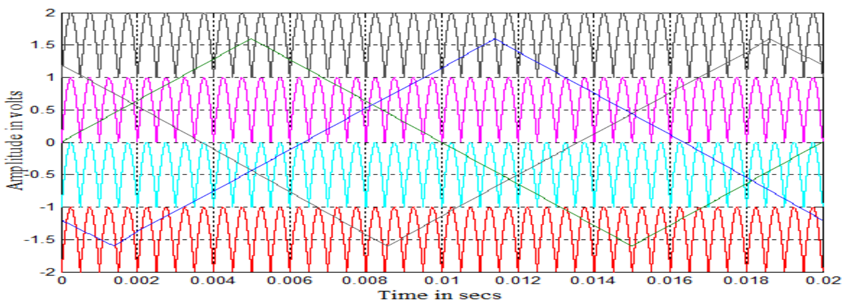

Figure 19. Sample Triangular Wave Reference Signal

f) Trapezoidal Amalgamated Reference

In this scheme triangular carrier and trapezoid modulating signals are used (Figure 20). The intersections between the trapezoid signals and carrier signal defines the switching instants of the PWM pulse. These signals can then be used to derive the actual gating signals for the power devices in the inverter module.

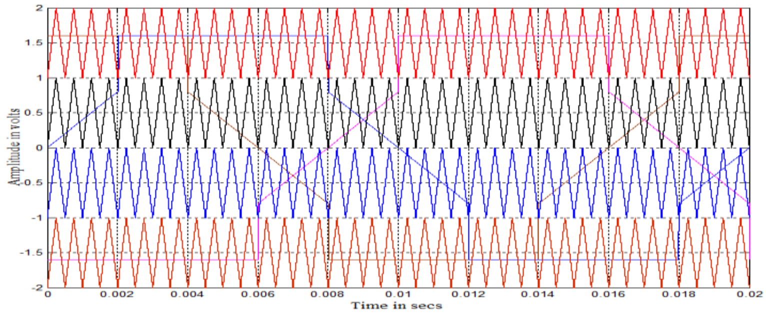

Figure 20. Sample TAR reference signal

4) Unipolar Triangular Carrier

The reference wave in the unipolar strategy may be a rectified sinusoid or two sine references with 180 degrees phase shift or third harmonic injection or 60 degree PWM or stepped wave or trapezoidal amalgamated or discontinuous PWM. The multi-carriers triangular or inverted sine are positioned only above zero level. For an m-level inverter using unipolar multicarrier technique, (m-1)/2 carriers with the same frequency f_c and same peak-to-peak amplitude A_c are used. The reference wave has the amplitude A_m and frequency f_m and it is placed with zero as reference. The different types of unipoalr carrier arrangements are:

a) UPDPWM
b) UAPODPWM
c) UCOPWM
d) UVFPWM
e) UPSPWM

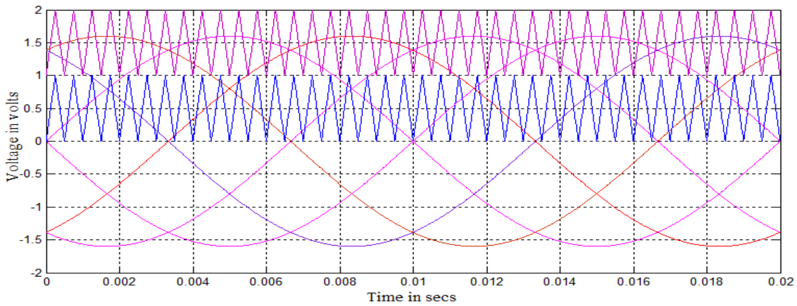

Figure 21. Sample multi-carrier arrangement for UPDPWM strategy

5) Unipolar Inverted Sine Carrier

6) Unipolar or Rectified Reference

a) Sinusoidal Reference
b) Third Harmonic Reference
c) 60 degree Reference
d) Stepped Wave Reference
e) Triangular Reference
f) Trapezoidal Amalgamated Reference

7) Bipolar Hybrid Carrier

a) PD + APOD
b) PD + CO
c) PD + PS
d) PD + VF
e) APOD + CO

This strategy (Figure 22) requires each of the two carrier waves in the upper half side to be phase displaced from each other by 180 degrees alternately. This strategy uses two triangular carriers in phase in the lower side (Figure 22).

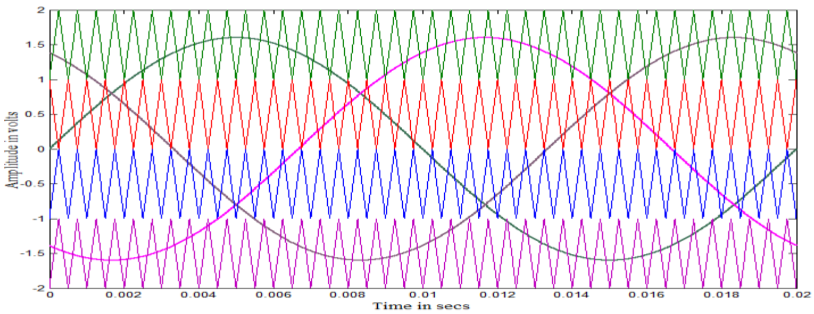

Figure 22. Sample multi-carrier arrangement for (APOD+CO) PWM strategy

a) APOD + PS
b) APOD + VF
c) CO + PS
d) CO + VF
e) PS + VF

8) Unipolar Hybrid Carrier

a) Triangular + Inverted sine

9) Bipolar Hybrid Reference

The principle of this PWM strategy is to use several triangular carriers which are in phase. It can be seen that the different references are used in the lower half side and upper half side.

a) Sine + THI

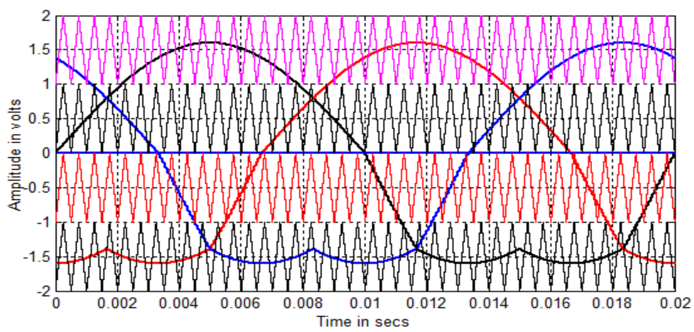

Figure 23. Sample hybrid reference arrangement

b) Sine + 60 degree
c) Sine + Stepped
d) Sine + TAR
e) Sine + Triangular
f) THI + 60 degree
g) THI + Stepped
h) THI + TAR

i) THI + Triangular
j) 60 degree+ Stepped
k) 60 degree + TAR
l) 60 degree + Triangular
m) Stepped + TAR
n) Stepped + Triangular
o) TAR + Triangular

10) Unipolar Hybrid Reference

a) Sine + THI
b) Sine + 60 degree
c) Sine + Stepped
d) Sine + TAR
e) Sine + Triangular
f) THI + 60 degree
g) THI + Stepped
h) THI + TAR
i) THI + Triangular
j) 60 degree+ Stepped
k) 60 degree + TAR
l) 60 degree + Triangular
m) Stepped + TAR
n) Stepped + Triangular
o) TAR + Triangular

11) Bipolar Variable Amplitude Carrier

Four carriers used for the chosen five level inverter are not equal in amplitude. Intermediate carriers below and above zero level have half the amplitude of the outermost two carriers. The Variable Amplitude Alternate Phase Opposition Disposition PWM (VAAPODPWM) strategy (Figure 24) is same as APODPWM method except that intermediate carriers are having variable amplitude compared to upper and lower carriers. In this strategy, carriers are seemed to be invert their phase in turn from previous ones and this same procedure is repeated above and below the zero levels.

a) VAAPOD

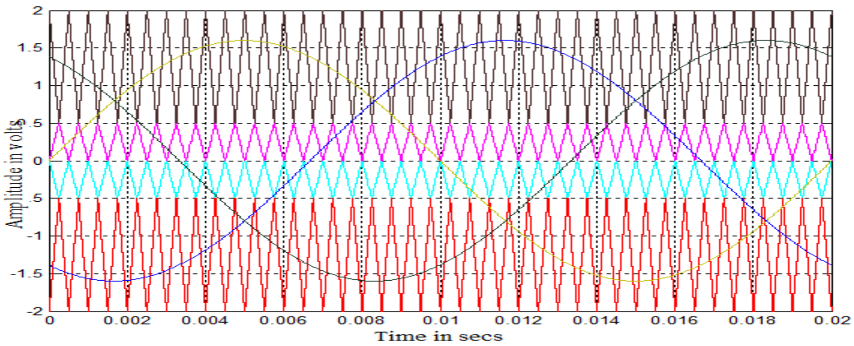

Figure 24. Sample multi-carrier arrangement for VAAPOD PWM strategy

b) VACOAPOD
c) VACOPD
d) VACOPOD
e) VACOPWM – 1
f) VACOPWM – 2
g) VACOPWM – 3
h) VACOPWM – A
i) VACOPWM – B

j) VACOPWM – C
k) VACOPWM – D
l) VACOVF
m) VAPD
n) VAPOD
o) VAVF

12) Unipolar Variable Amplitude Carrier

a) VAAPOD
b) VACOAPOD
c) VACOPD
d) VACOPOD
e) VACOPWM – 1
f) VACOPWM – 2
g) VACOPWM – 3
h) VACOPWM – A
i) VACOPWM – B
j) VACOPWM – C
k) VACOPWM – D
l) VACOVF
m) VAPD
n) VAPOD
o) VAVF

3. Conclusion

Various non PWM and PWM methods are discussed in this paper for MLI. Each and every tech is having some advantages and disadvantage. The non PWM methods like flip flop, embedded and Selective Harmonic Elimination are used for fixed speed drive application. Whereas PWM methods are used for the variable speed drive applications. As per the various references sinusoidal reference with carrier will produce less THD and less Vrms. Other than sine reference other references produce more THD with more Vrms. As per the carrier the triangular carrier is better compared to other carriers. Variable amplitude carriers are used to improve he THD and fundamental rms value to certain extent.

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