Development of Multi-Carrier PWM Technique for Multilevel Inverters

Sara Laali[1], Karim Abbaszadeh[2], Hamid Lesani[3]
[1,2]Islamic Azad University, South Tehran Branch, Tehran, Iran
[2]Department of Electrical Engineering, K. N. Toosi University of Technology, Tehran, Iran
[3]School of Electrical & Computer Engineering, University of Tehran, Tehran, Iran
Emails: [1]s.laali@yahoo.com, [2]Abbaszadeh@eetd.kntu.ac.ir, [3]lesani@ut.ac.ir

Abstract— Multilevel voltage source inverters are emerging as a new breed of power converter options for high-power applications. Various topologies and modulation strategies of multilevel inverters have been proposed. In this paper, the different multi-carrier PWM techniques are investigated and several interesting characteristics of them are revealed. A new method of multi-carrier PWM strategies is also proposed and compared with different conventional multi-carrier PWM techniques. Reduction of total harmonics distortion (THD) and improvement of the harmonic spectrum of inverter output voltage are some advantages of the proposed control method. The simulation results based on PSCAD/EMTDC software are presented to validate the capabilities of the proposed modulation method.

Keywords: Multilevel inverter; multi-carrier PWM techniques; phase disposition PWM; phase opposition disposition PWM; alternate phase opposition disposition PWM.

I. INTRODUCTION

Numerous industrial applications have begun to require higher power apparatus in recent years. Some medium voltage motor drives and utility applications require medium voltage and megawatt power level. For a medium voltage grid, it is troublesome to connect only one power semiconductor switch directly. As a result, a multilevel power inverter structure has been introduced as an alternative in high power and medium voltage situations. A multilevel inverter not only achieves high power ratings, but also enables the use of renewable energy sources. Renewable energy sources such as photovoltaic, wind, and fuel cells can be easily interfaced to a multilevel inverter system for a high power application [1].

A multilevel converter is a power electronic system that synthesizes a desired output voltage from several levels of dc voltages as inputs. Compared with the traditional two-level voltage converter, the primary advantage of multilevel converters is their smaller output voltage step, which results in high power quality, lower harmonic components, better electromagnetic compatibility, and lower switching losses [2].

The first topology introduced was the series H-bridge design [3], but several configurations have been obtained for this topology as well [4-5]. Since this topology consist of series power conversion cells, the voltage and power level may be easily scaled. An apparent disadvantage of this topology is the large number of isolated voltages required to supply each cell. The H-bridge topology was followed by the diode-clamped converter which utilized a bank of series capacitors [6]. Another fundamental multilevel topology, the flying capacitor, involves series connection of capacitor clamped switching cells [7]. This topology has several unique and attractive features when compared to the diode-clamped inverter. One feature is that added clamping diodes are not needed. Furthermore, the flying capacitor inverter has switching redundancy within the phase which can be used to balance the flying capacitors so that only one dc source is needed [2].

Different modulation strategies have been used in multilevel power conversion applications within the technical literature. They can generally be classified into three categories: fundamental frequency switching, space vector PWM (SVPWM) and multi-carrier PWM techniques. This paper focused on the multi-carrier PWM technique which has been extended using multiple references. Multi-carrier PWM techniques can be categorized into three groups: phase disposition PWM (PD-PWM), phase opposition disposition PWM (POD-PWM) and alternate phase opposition disposition PWM (APOD-PWM) techniques. In these modulation strategies, the reference waveform is sampled through a number of carrier waveforms displayed by contiguous of the reference waveform amplitude [8-11].

The different multi-carrier PWM modulation strategies for multilevel inverters will be reviewed in this paper. This paper is organized into the following way: first, the different multi-carrier PWM methods are described and several interesting characteristics of them are revealed. After this, a new method of multi-carrier PWM technique is proposed. The proposed method is compared with different conventional multi-carrier PWM techniques based on simulation results using PSCAD/EMTDC software.

II. CONVENTIONAL CARRIER-BASED PWM METHODS

Multicarrier PWM techniques entail the natural sampling of a single modulating or reference waveform typically being sinusoidal, through several carrier signals typically being triangular waveforms [9].

In order to describe the different multi-carrier PWM methods the following definitions should be considered:

- The frequency modulation index is defined as $m_f = f_c / f_r$, where f_c is the frequency of carrier signals and f_r is the frequency of the reference signal.
- The amplitude modulation index is defined as $m_a = A_r / A_c$, where A_r is the amplitude of reference signals and A_c is the peak to peak value of the carrier signal [8].

A. PD-PWM method

The PD-PWM method, as one of the carrier-based PWM methods, is based on a comparison of a sinusoidal reference waveform with vertically shifted carrier waveforms. The PD-PWM method uses $N-1$ carrier signals to generate the N-level at output voltage. The carrier signals have the same amplitude and the same frequency and are in phase. The sinusoidal reference wave has a frequency f_r and an amplitude A_r. At each instant, the result of the comparison is decoded in order to generate the correct switching function corresponding to a given output voltage level. In PD-PWM method, with even and odd m_f, the significant harmonic energy is concentrated on the carrier frequency. For instance, with $m_f = 39$, the significant harmonic energy is in 39th harmonic. The PD-PWM method yields only odd harmonics for odd m_f and yields odd and even harmonics for even m_f. Also, this method yields quarter wave symmetry only for odd m_f [8-11].

B. POD-PWM method

In the POD-PWM method the carrier signals above the zero axis are in phase. The carrier signals below zero axis are also in phase but 180 degrees phase shifted. For even and odd values of frequency modulation index, the significant harmonics are located in two sidebands around the carrier frequency. There is no harmonics at f_c. For instance, with $m_f = 39$ the significant harmonics are 28th and 40th harmonics For odd m_f, the POD-PWM waveform has odd symmetry resulting in only even harmonics. For even m_f, the waveforms have quarter wave symmetry resulting in only odd harmonics [8-11].

C. APOD-PWM method

This technique requires each of the $N-1$ carrier waveforms for an N-level phase waveform, to be phase displaced from each other by 180 degrees alternately. For even and odd m_f, the most significant harmonics are sidebands of the carrier frequency. But there is no harmonics f_c. For odd m_f, the APOD-PWM waveform has odd symmetry resulting in only even harmonics. For even m_f, the waveforms have quarter wave symmetry resulting in only odd harmonics [8-11].

III. PROPOSED MODULATION METHOD

For reducing the number of carrier signals and also improvement of the THD and harmonic spectrum of inverter output voltage, a new modulation strategy is proposed in this paper. The proposed multi-carrier PWM method uses $(N-1)/2$ carrier signals to generate the N-level at output voltage. The carrier signals have the same amplitude, A_c and the same frequency, f_c, and are in phase. The sinusoidal reference wave has a frequency f_r and an amplitude A_r. In the proposed method, the sinusoidal reference and its inverse are used for generating the required gate signals. The frequency of the output voltage is determined by the frequency of the sinusoidal reference waveform. The amplitude of the fundamental component of the output voltage is determined by the amplitude modulation index, m_a.

Fig. 1 shows the proposed multi-carrier PWM method for a single-phase 5-level inverter. As this figure shows, the proposed method uses two reference signals and two carrier signals. This method is based on a comparison of the sinusoidal reference waveforms with carrier waveforms. For even and odd values of frequency modulation index, m_f, the significant harmonics are located in two sidebands around the frequency, $2f_c$. As a result, the frequency spectrum of the output voltage is improved. So, the size of the required filter will be small. It is important to note that the design of filter is not the objective of this work. Reduction of the THD of the output voltage is other important advantage of the proposed method. It is noticeable that the conventional modulation methods generate the significant harmonics in two sidebands around the carrier frequency, f_c.

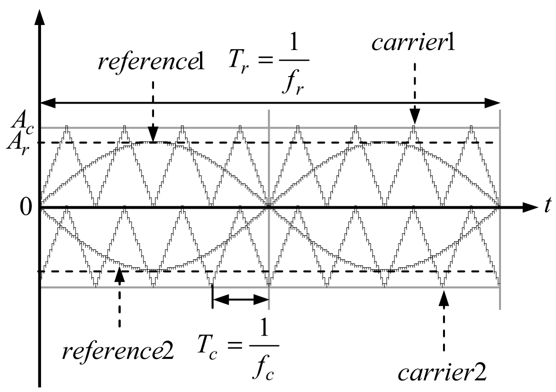


Fig. 1. Proposed multi-carrier PWM method for a single-phase 5-level inverter

IV. SIMULATION RESULTS

To examine the performance of the proposed control method, a single-phase 5-level cascaded inverter is simulated. The PSCAD software has been used for simulation. Fig. 2 shows the 5-level cascaded inverter topology. This inverter consists of two full-bridge converters. The amplitudes of dc voltage sources are considered 100V. It is assumed that the inverter is adjusted to produce a 50Hz, 5-level staircase waveform. The amplitude of the fundamental component is considered 160V. Test has been made on R-L load ($R = 20\Omega$ and $L = 55mH$). Fig. 3 shows the control block diagram of the inverter based on the proposed control method. As shown in this figure, both switches on a leg cannot be on simultaneously, because a short circuit across dc voltage sources would be produced.

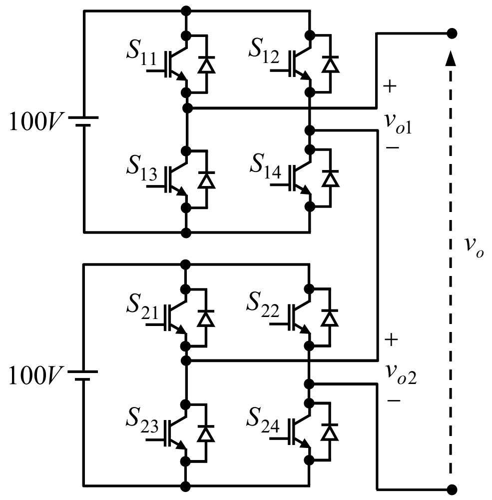


Fig. 2. Five-level cascaded multilevel inverter

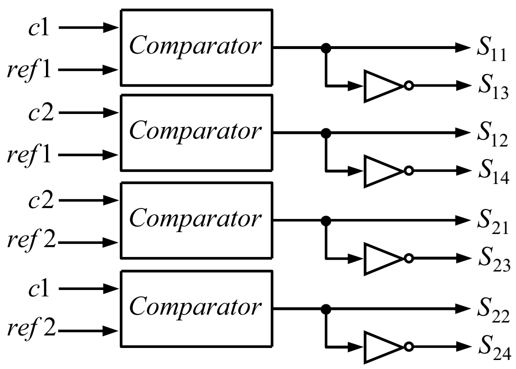


Fig. 3. Control block diagram

Fig. 4 shows the references and carriers waveforms. As this figure shows, the amplitude and frequency of the reference waveform have been considered $A_r = 0.8pu$ and $f_r = 50Hz$, respectively. The frequency of the multi-carrier is assumed $f_c = 500Hz$. Fig. 5 shows the gate signals of the IGBTs. Figs. 6-8 show the simulation results for full-bridges and output voltages and current. As can be seen from the waveforms, the output current is almost sinusoidal. Since the load of the inverter is almost a low pass filter (R-L), then the output current contain less high order harmonics than the output voltages. The frequency spectrum of the output voltage and current is shown in Figs. 9-10, respectively. The output voltage waveform of the inverter as shown in Fig. 9 is made up from a fundamental frequency sine wave and a few numbers of harmonics. Fig. 9 shows that the amplitude of the fundamental component is 159.81V that has good agreement with the forecasted amplitude of the output voltage. The frequency spectrum of the output voltage shows that the significant harmonics are located in two sidebands around the 20th harmonic. The THDs of the output voltage and current based on simulation are 31.79% and 2.53%, respectively. To generate a desired output voltage with best quality of the waveform, the frequency of the carrier signals should be increased.

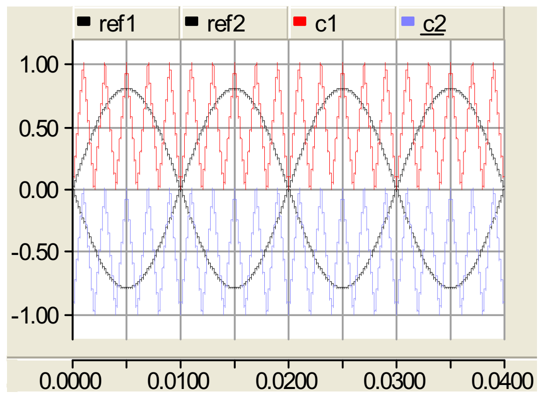
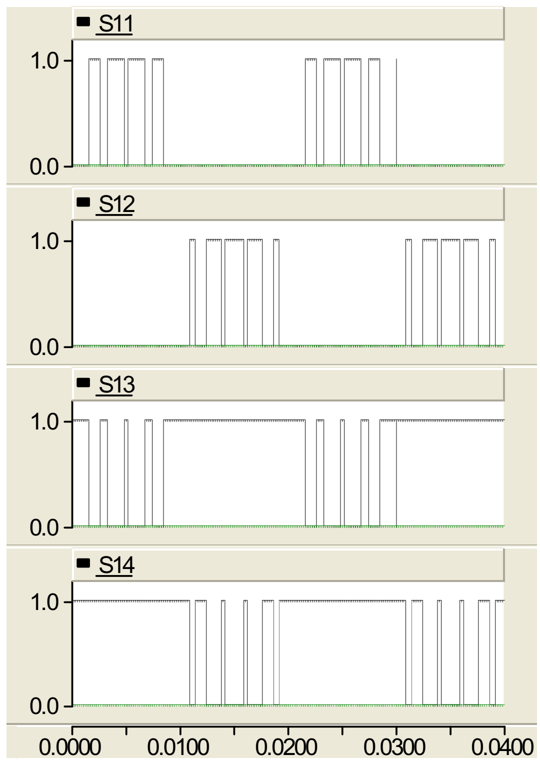
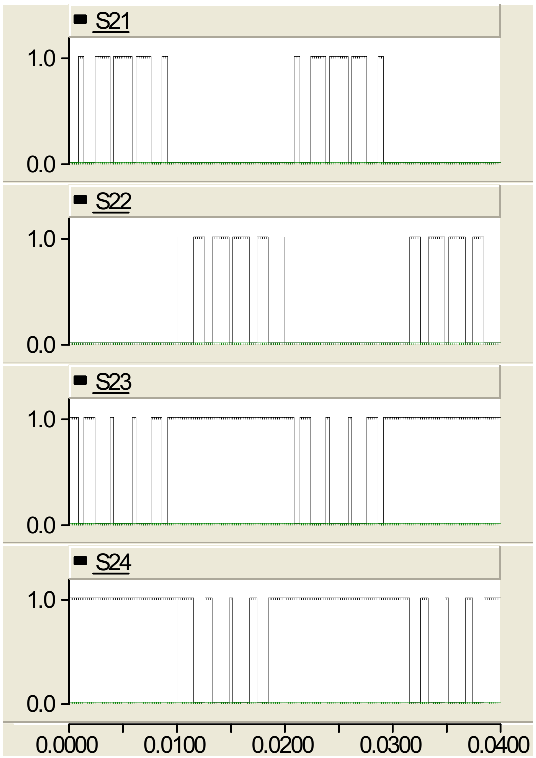


Fig. 4. References and carriers waveforms for a 5-level inverter based on the proposed method



(a)



(b)

Fig. 5. Gate signals; (a) First full-bridge; (b) Second full-bridge

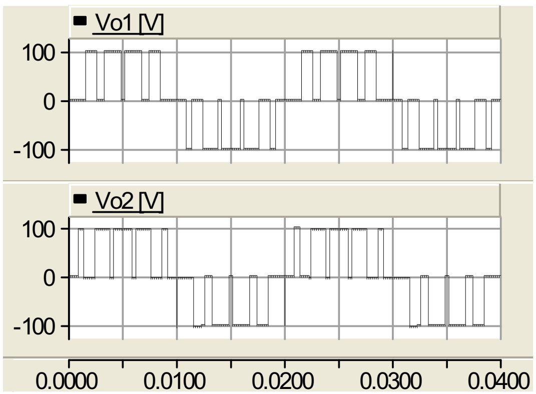


Fig. 6. Full-bridges output voltages

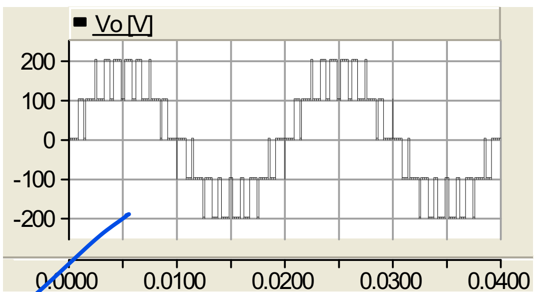


Fig. 7. Inverter output voltage

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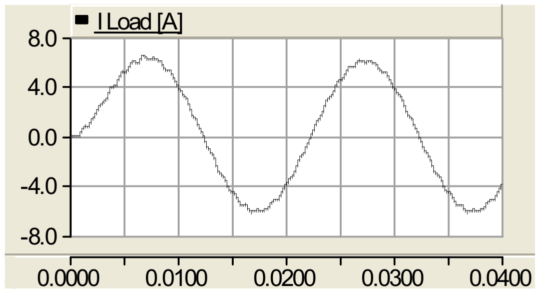

Fig. 8. Inverter output current

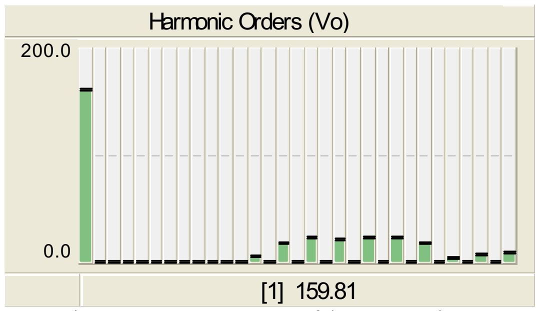

Fig. 9. Frequency spectrum of the output voltage

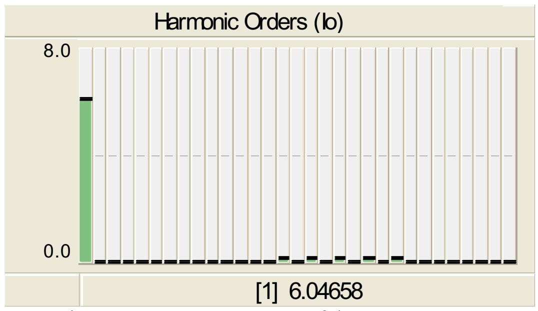

Fig. 10. Frequency spectrum of the output current

V. COMPARISON OF THE PROPOSED METHOD WITH CONVENTIONAL CARRIER-BASED PWM METHODS

For revealing the advantages of the proposed method in comparison with the conventional multi-carrier PWM methods, it is necessary to consider the frequency spectrums of the output voltages. Fig. 11 shows the THDs of different multi-carrier PWM methods versus m_f for $m_a = 0.8$. Fig. 12 shows the THDs of different multi-carrier PWM methods versus m_a for $m_f = 22$. As Figs. 11 and 12 show, for different values of m_f and m_a, the THD of the proposed method is less than the conventional multi-carrier PWM methods.

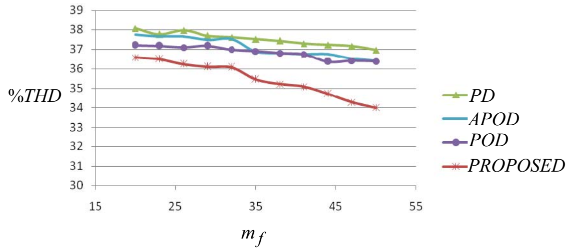

Fig. 11. THDs of different multi-carrier PWM methods versus m_f for $m_a = 0.8$

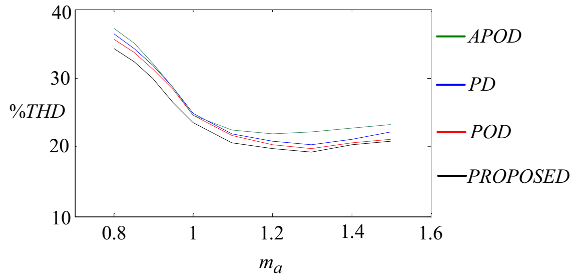

Fig. 12. THDs of different multi-carrier PWM methods versus m_a for $m_f = 22$

VI. CONCLUSION

In this paper, a new method of multi-carrier PWM method is proposed. The significant harmonics in conventional methods are located in two sidebands around m_f and it's multiple. But in the proposed method, the significant harmonics are located in two sidebands around $2m_f$ and it's multiple. As a result, the size of the required filter will be small. Reduction of the THD of the output voltage is other important advantage of the proposed method in comparison with other conventional multi-carrier PWM methods.

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