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ORIGINAL ARTICLE

Performance Comparison of PWM Methods for 27-Level Hybrid Multilevel Inverters

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ABSTRACT

Multilevel inverters have become more popular due to reduced switching losses, low costs, low harmonic distortion and high-voltage capability when compared to traditional PWM inverters. A new family of multilevel inverters that has decreased the number of separated DC sources has emerged named as hybrid multilevel inverter. In this study, theories and applications of four PWM modulation methods for 27 level hybrid multilevel inverters are examined. The comparative case studies are presented to validate the examined modulation technique through harmonic spectrum analysis, output voltage magnitude, THD, WTHD and simulation using Power System Computer Aided Design Program (PSCAD).

Key Words: *Hybrid multilevel inverters, H-bridge inverters, Reference signal generation, Pulse width modulation (PWM).*

1. INTRODUCTION

Multilevel inverters have gained much attention in recent years due to their various advantages. The general concept of multilevel inverters involves the utilizing a higher number of power electronics switches to perform the power conversion in small voltage steps. The small voltage steps lead to obtain the low harmonic distortion and switching losses, devices possessing low voltage ratings and higher efficiency. Also, it performs the reduction of $\partial v/\partial t$ stresses on the load and gives the possibility of working with low speed power electronic switches. Such multilevel inverter topology permits a significant reduction of the output filter and an improvement of the efficiency [1-2]. The industrial drives and distributed generation resources include the multilevel inverters [3]. Recently, multilevel inverter topology has been applied to low-voltage applications, as well [4]. Diode-clamped, flying capacitor and cascaded (H-bridge) are the fundamental multilevel inverter topologies [5-7]. Among these inverters, the cascaded H-bridge inverter is useful for practical applications owing to the advantages that the modularized circuit layout, it does not need extra clamping diodes or voltage balancing capacitors and it requires the reduced number of components to achieve the same number of output

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voltage levels among the conventional multilevel inverters [8]. Another important topic is the increasing the level number of multilevel inverter. Thus, the harmonic distortion can be reduced as much as possible while keeping low switching frequency and switching losses.

The hybrid multilevel is the new structures, where the cascaded series inverters have different internal DC bus voltages, use different switching devices and are modulated quite differently in [9]. The hybrid multilevel inverter generates a larger number of levels with the same number of power devices of the cascaded multilevel inverter, uses more effectively the natural switching speed and voltage blocking characteristics are different types of switching devices. If the level of hybrid multilevel inverters increases, the total harmonic distortion (THD) of the output voltage decreases and the quality of the output AC voltage improves [10]. The methods that are the selective harmonic elimination, space vector modulation and sinusoidal PWM are the commonly used in the multilevel inverters [11-13]. Many modulation algorithms have been adapted or created for hybrid multilevel inverters in the literature. However, the conventional PWM method, modified phase disposition method, modified phase opposition disposition method and phase shifted carrier PWM method were adapted to cascaded multilevel inverters but not adapted to hybrid multi-level inverters [14-15].

In this paper, the important PWM methods are applied to a 27 level hybrid H-bridge inverter [14-16]. The operation principles of these methods are verified by using PSCAD. Harmonic spectrums, THD and weighted THD (WTHD) values are also presented with the help of designed PSCAD-MATLAB interface. Finally, simulation results of presented methods are discussed and compared.

2. TOPOLOGY OF THE HYBRID MULTILEVEL INVERTER

Hybrid multilevel inverter is used with an order-3 configuration varies in DC source ratio with 1/3/9 [9]. The inverter given in Figure 1 consists of three H-bridge cells and DC link voltage among the stages has the relationship of V_{DC}, $3V_{DC}$ and $9V_{DC}$. By using three H-bridge cells fed with separate DC sources and controlling the switching of the cells, an output voltage with various levels can be generated. The output voltages of H-bridge cell are given in Table 1.

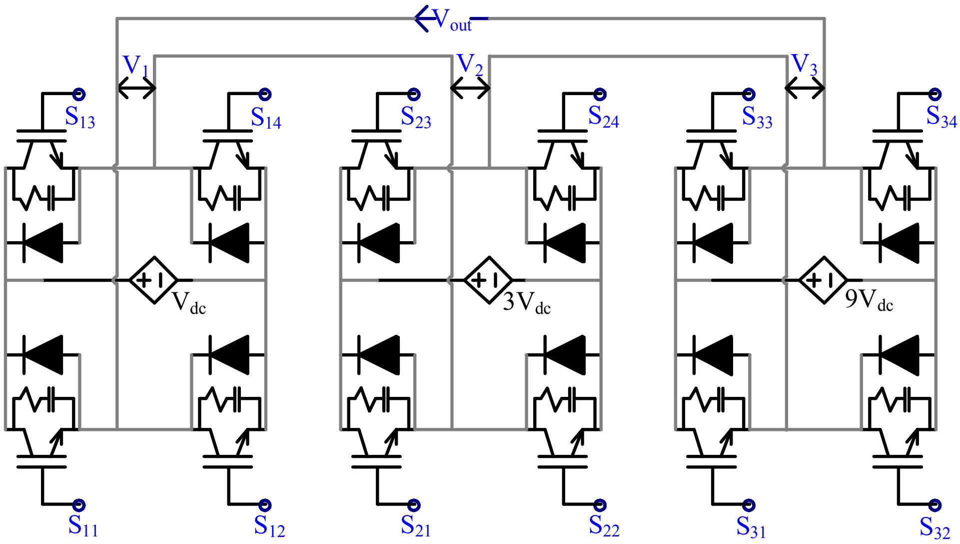

Figure 1. Hybrid multilevel inverter topology with the ratio of 1/3/9.

P and *N* denote the output voltages of the stages of V_{DC}, $3V_{DC}$ and $9V_{DC}$ with positive and negative voltage polarities, respectively. *Z* denotes that the related stage is in a freewheeling state. Figure 2 illustrates the voltage polarities (positive, zero and negative polarities) for the first H-bridge cell according to the switching states.

27 output levels can be obtained by various switching states of each H-bridge cell. The switching states and the output values hybrid inverter are given in Table 2. The inverter switching losses of PWM inverters with H-bridge cell are significantly reduced compared with other methods [9].

Table 1. The output voltage of each H-bridge cell.

Output Voltage of Each Cell	Value	States	
		Switches	Polarity
V_1 (H-bridge cell 1)	$+1V_{dc}$	S_{11}- S_{14} ON	P
	$0V_{dc}$	S_{12}- S_{14} ON	Z
	$-1V_{dc}$	S_{12}- S_{13} ON	N
V_2 (H-bridge cell 2)	$+3V_{dc}$	S_{21}- S_{24} ON	P
	$0V_{dc}$	S_{22}- S_{24} ON	Z
	$-3V_{dc}$	S_{22}- S_{23} ON	N
V_3 (H-bridge cell 3)	$+9V_{dc}$	S_{31}- S_{34} ON	P
	$0V_{dc}$	S_{32}- S_{34} ON	Z
	$-9V_{dc}$	S_{32}- S_{33} ON	N

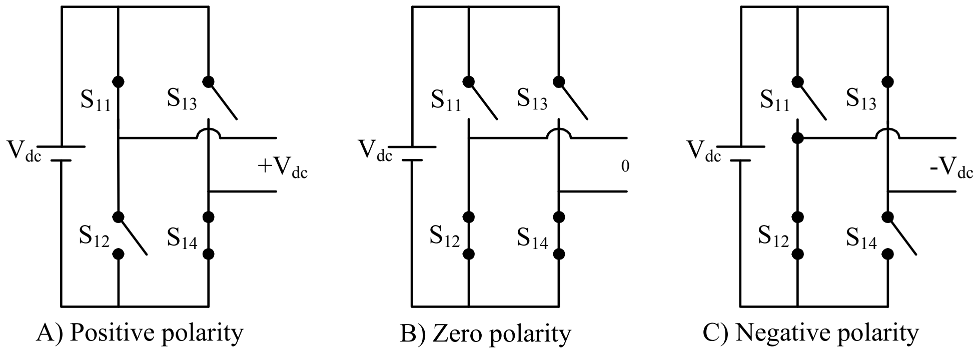

Figure 2. Output voltage polarities and switching states for the first H-bridge cell.

Table 2. Voltage levels of hybrid multilevel inverter with Polarities.

V_{out}	V_1	V_2	V_3	V_{out}	V_1	V_2	V_3
-13 V_{dc}	N	N	N	+13 V_{dc}	P	P	P
-12 V_{dc}	Z	N	N	+12 V_{dc}	Z	P	P
-11 V_{dc}	P	N	N	+11 V_{dc}	N	P	P
-10 V_{dc}	N	Z	N	+10 V_{dc}	P	Z	P
-9 V_{dc}	Z	Z	N	+9 V_{dc}	Z	Z	P
-8 V_{dc}	P	Z	N	+8 V_{dc}	N	Z	P
-7 V_{dc}	N	P	N	+7 V_{dc}	P	N	P
-6 V_{dc}	Z	P	N	+6 V_{dc}	Z	N	P
-5 V_{dc}	P	P	N	+5 V_{dc}	N	N	P
-4 V_{dc}	N	N	Z	+4 V_{dc}	P	P	Z
-3 V_{dc}	Z	N	Z	+3 V_{dc}	Z	P	Z
-2 V_{dc}	P	N	Z	+2 V_{dc}	N	P	Z
-1 V_{dc}	N	Z	Z	+1 V_{dc}	P	Z	Z
0 V_{dc}	Z	Z	Z				

3. COMMON PWM METHODS FOR THE HYBRID MULTILEVEL INVERTERS

There are many multi-carrier based PWM methods proposed for the multilevel inverters. The widely used these PWM methods are known as phase shifted (PhS), phase disposition (PD), phase opposition Disposition (POD) and Alternative Phase Opposite Disposition (APOD) [14-15]. In these methods, the carrier signals are compared with the reference signal to calculate the switching positions (given in Table 2) of H-bridge cells given in Figure 1. The basic sinusoidal PWM method is used in the calculation of the switching positions for H-bridge cells.

3.1. Conventional PWM Method (CPWM)

A triangular carrier signal is used for all voltage levels in CPWM method. The amplitude of the triangular equals to maximum value of the reference signal. The frequency of the carrier signal can be selected arbitrarily between 10 to 100 times of the reference signal frequency. The comparison of the reference signal with the carrier signal for CPWM method and the output waveform of the hybrid-multilevel inverter are illustrated in Figure 3.

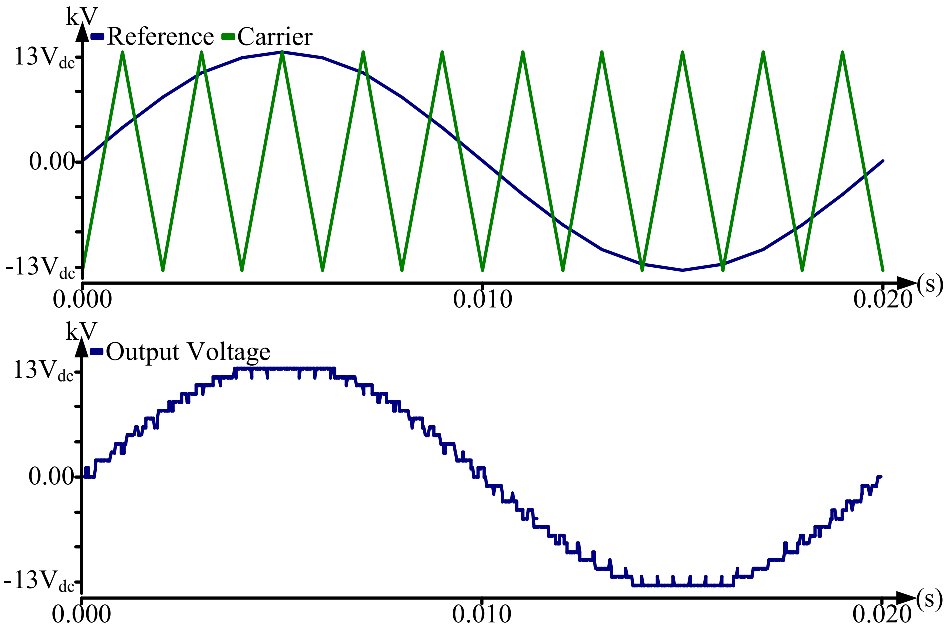

Figure 3. Basic representation of CPWM and the output voltage of the inverter.

3.2. Modified Phase Disposition Method (MPD)

The multi-carrier signals are used in this method. The number of used carrier signals is defined proportional with the inverter level. For instance, 27 triangular carrier signals are used for hybrid inverter. The amplitudes of the carrier signals ($IV_{crr}I$) are calculated by using (1).

$$IV_{crr}I = \frac{IV_{REF}I}{n} \tag{1}$$

where, n is the level of the hybrid inverter and $IV_{crr}I$ is the maximum value of the reference signal.

For each level of the hybrid-multilevel inverter, one carrier signal is used. The reference signal and the related carrier signal are compared for each interval between two levels. IGBTs are switched by the control unit according to the situations that the reference signal is higher, equal or lower than the related carrier signal. The comparison of the reference signal with the carrier signal for MPD method and the output waveform of the hybrid-multilevel inverter are illustrated in Figure 4.

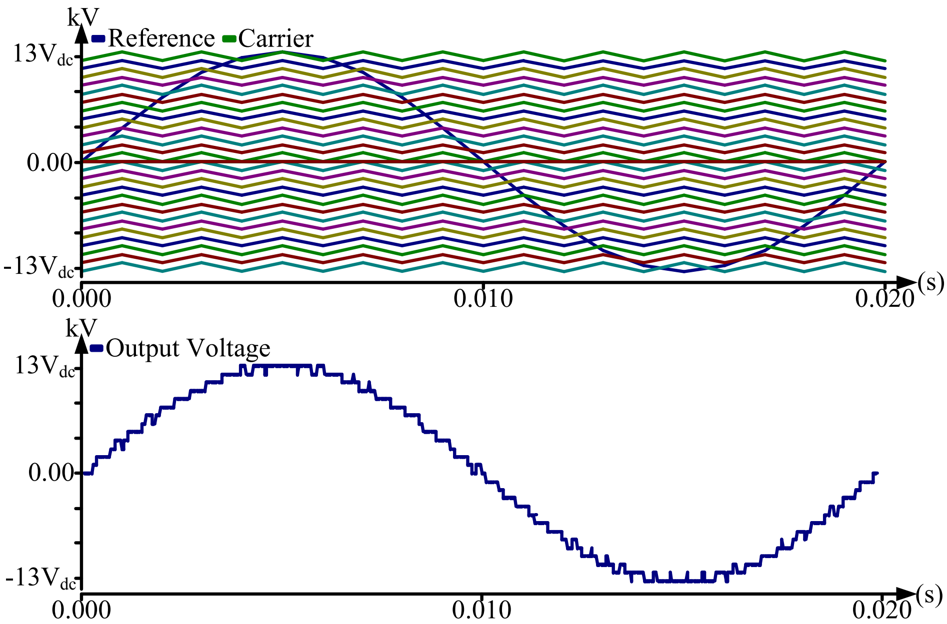

Figure 4. Basic representation of MPD and the output voltage of the inverter.

3.3. Modified Phase Opposition Disposition Method (MPOD)

The similar processes with MPD method are used in MPOD method. The difference of MPOD method from MPD method is the multiplication of the carrier signals for negative cycles with "-1". The comparison of the reference signal with the carrier signal for MPOD method and the output waveform of the hybrid-multilevel inverter are illustrated in Figure 4.

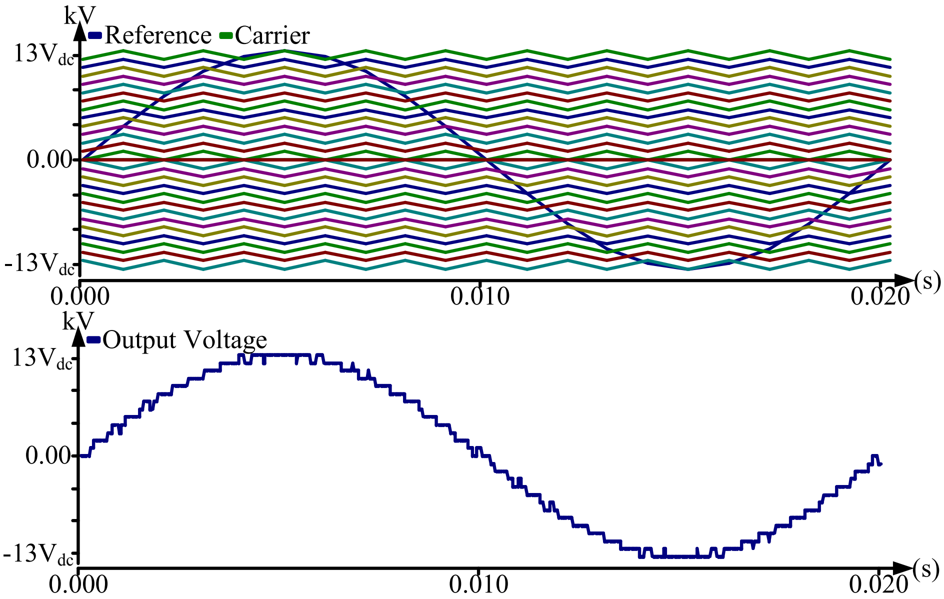

Figure 5. Basic representation of MPOD and the output voltage of the inverter.

3.4. Modified Phase Shifted Method (MPS)

The similar processes with MPD method are used in MPs method. The difference of MPs method from MPD method is the using of the phase-shifted carrier signals. All carrier signals have the same amplitude and frequency but they are phase shifted by 90 degrees to each other [14]. The comparison of the reference signal with the carrier signal for MPS method and the output waveform of the hybrid-multilevel inverter are illustrated in Figure 5.

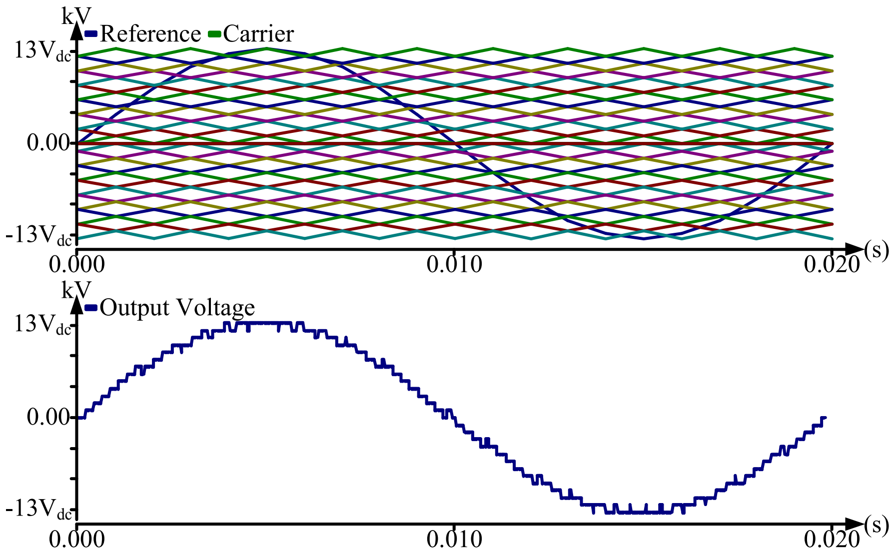

Figure 6. Basic representation of MPOD and the output voltage of the inverter.

4. CASE STUDIES AND DISCUSSIONS

PSCAD simulation package is used to simulate the test system given in Figure 1 and to evaluate the performances of the methods given above. Harmonic spectrums and THD values are calculated and presented via PSCAD. The carrier signal frequency used in PWM methods is selected as 3kHz for Case 1. The reference signal amplitude is selected as 0.310kV. The voltage value of interval between levels is calculated as 0.0238kV. All the modulation methods generate 27 level output voltage. The case studies are given as flows:

Case 1: Comparison of the harmonic spectrums of the output voltages

In the case study, the harmonic spectrums of the output voltages for the methods are observed between 2^{nd} to 31^{th} harmonics given in Figure 7. In the harmonic spectrums, the fundamental harmonic is eliminated to observe the other harmonic components in detail. Then, the following results can be concluded.

- Each harmonic component of the methods is less than %1.5 of the fundamental harmonic.
- The values of even harmonics are relatively high in CPWM and MPD methods.
- In CPWM, the values of harmonic components between 2^{nd} to 14^{th} are higher than the other methods.
- In MPOD, the even harmonics are only observed in harmonic spectrum of the output voltage waveform.

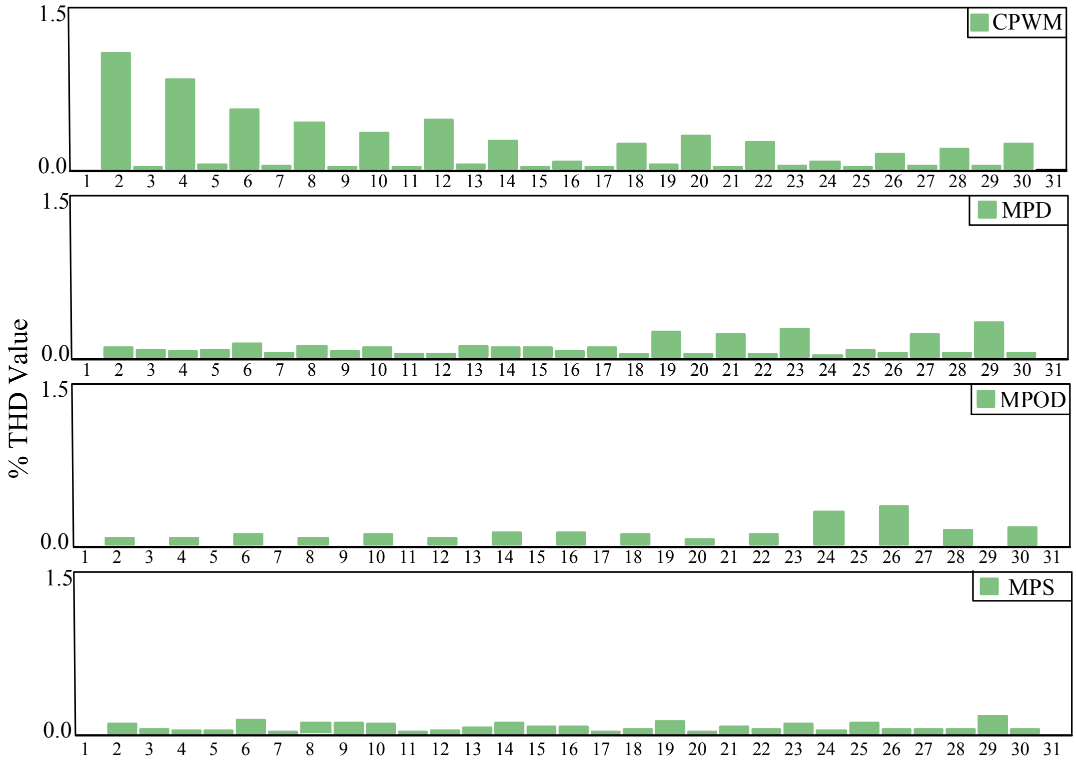

Figure 7. Harmonic spectrums of output voltage for all methods (for m_a=1).

Case 2: Comparison of THD values of the output voltages

In this case study, THD values of the output voltage waveforms are observed and compared with each other for their performance evaluations. The carrier signal frequency used in PWM methods is selected as 1, 2 and 2.5kHz for Case 2. THD results of the methods are calculated by using (2).

$$THD = \sqrt{\sum_{n=2}^{\infty}\left(h^{(n)}/h^{(1)}\right)^2} \qquad (2)$$

where h_1 is the fundamental harmonic and n is the indices of harmonic.

The performance comparisons of the methods are performed by changing the magnitude of the voltage source (m). For instance, m=0.5, m=0.75 and m=1.0 mean that the values of the voltage source (line-line) are 0.190kV, 0.285kV and 0.380kV, respectively. 32^{nd} order of harmonics is taken into account during the calculation of THD values. The results of the performance comparison are given in Table 1.

Table 1. THD values of output voltage.

PWM Methods	**THD Values (%)**								
	PWM Frequency: 1kHz			**PWM Frequency**: 2kHz			**PWM Frequency**: 2.5kHz		
	m=0.5	m=0.75	m=1.0	m=0.5	m=0.75	m=1.0	m=0.5	m=0.75	m=1.0
CPWM	8.708	4.855	3.252	3.391	1.772	1.682	3.321	1.681	1.726
MPD	7.790	5.083	3.419	2.370	1.844	1.536	1.921	1.116	1.263
MPOD	8.247	5.301	3.422	2.905	2.063	1.822	1.953	1.185	1.327
MPS	7.184	4.227	2.628	4.022	3.105	2.553	2.354	2.483	2.167

According to the Table 1, the following results can be obtained from THD values of the modulation methods.

- The increasing of *m* is resulted with the decreasing of THD value for all methods.
- The variation of THD value decreases with the higher PWM frequency.
- MPD and MPOD methods are kept THD for all *m* values below %2 at 2.5kHZ PWM frequency.

CONCLUSIONS

In this paper, the modulation methods based on PWM are adopted to 27 level hybrid multilevel inverters to provide output voltage with 27-levels. The magnitude of reference signal is divided to hybrid inverter levels and switching of IGBTs for each H-bridge cell is determined according to these levels. According to the results of Case 1, the values of harmonic components between 2^{nd} to 14^{th}, are higher than the other methods in CPWM method. The even harmonics are only observed in the harmonic spectrum of the output voltage waveform in MPOD method. According to the results of case 2, the best performances are obtained with MPS method for 1kHz and MPD method for 2kHz and 2.5kHz. The common properties of PWM modulation techniques are the reduction of switching losses with better harmonic indices.

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