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Carrier-Based PWM Techniques for Multi-Level Inverters: A Comprehensive Performance Study

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Abstract

This work deals with a carrier based sinusoidal pulse width modulation strategies for three phase seven level cascaded H-bridge multilevel inverter. Sawtooth and triangular carriers are presented with the different reference signals i.e. sinusoidal reference, third harmonic injected sinusoidal reference and trapezoidal reference. Various modulation strategies like phase disposition pulse width modulation, phase opposition disposition pulse width modulation and alternate-phase opposition disposition pulse width modulation are implemented for different reference signals.

The various arrangements of sawtooth and triangular carriers are implemented based on the three different carrier arrangement techniques such as constant frequency, variable frequency and carrier overlapping. The comparison table of % total harmonic distortion content has also been included for different modulation index of each reference signal with various modulation strategies based on the different arrangements of the carriers. The work has been carried out and tested in MATLAB/SIMULINK platform and % total harmonic distortion present in phase voltage and line voltage for three different reference signals has also been studied as well.

1. INTRODUCTION

To obtain nearly sinusoidal output voltage from the conventional or classical voltage source inverter (VSI) with variable amplitude and frequency control is one of the major problem [1,2]. The problems like electromagnetic interferences (EMI), pulsating torques and power loss are some of the common problems produced in ac motor due to the current harmonics generated by non-sinusoidal output voltage of voltage source inverter. Thus, the harmonic reduction is a critical issue to be resolved for enhancing the performance of the VSI. In the year 1975, Baker and Banister introduced multi-level inverter [3]. The concept of multi-level inverter (MLI) deals with increase in the number of levels thereby increasing the steps of output voltages. These output voltages forms staircase structure thus reducing the harmonic distortion [4]. Multilevel inverter are recently popular due to its day-by-day grown up industrial applications with efficient power generation by use of renewable energy [5,6]. Low size of filter requirement in multilevel inverter with higher quality output voltages produces a much lesser harmonic content nearly sinusoidal output [7,8].

Among the three conventional multilevel voltage source inverters such as neutral-point (NPC-MLI) [9], cascaded H-bridge (CHB-MLI) [10] and flying capacitor (FC-MLI) [11], CHB-MLI started gaining attention for industrial applications and commercialization [12, 13]. Cascading the required number of single H-bridge inverter in series produces the multilevel output. CHB-MLI is widespread in the high power medium-voltage industries due to its modular structure and its continuous un-interrupted working under faulty module condition [14-17].

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The harmonic content in the output voltage of the MLI are also improved by pulse width modulation (PWM) techniques such as sinusoidal pulse width modulation (SPWM), selective harmonic elimination (SHE), space vector pulse width modulation [18-21]. Carrier based SPWM control techniques have been widely used due to its easier implementation.

This paper contains comprehensive analysis of harmonic content in the output voltage of three phase seven level inverter. Three different reference signals i.e. sinusoidal reference, third harmonic injected sinusoidal reference and trapezoidal reference are employed to study the variations of total harmonic distortion (THD) content in the output voltage for different arrangements of carrier signals i.e. Phase Disposition PWM (PD PWM), Phase Opposition Disposition PWM (POD PWM), Alternate Phase Opposition Disposition PWM (APOD PWM). Nevertheless, these carrier signals are further arranged in the three more different patterns i.e. Constant Frequency (CF), Variable Frequency (VF) and Carrier Overlapping (CO) and the THD content for phase voltage as well as line voltage are studied.

2. H-BRIDGE MULTI-LEVEL INVERTER

In the area of multilevel inverter, THD reduction has been a point of concern. Fig. 1 shows the circuit configuration of three phase seven level cascaded H-bridge inverters. Each H-bridge requires a DC source. As the H-bridge increases, the output voltage forms more sinusoidal staircase structure. The more the number of levels, the lesser becomes the THD. Application of multilevel inverters in industries depends on the economic cost, maintenance and reliability.

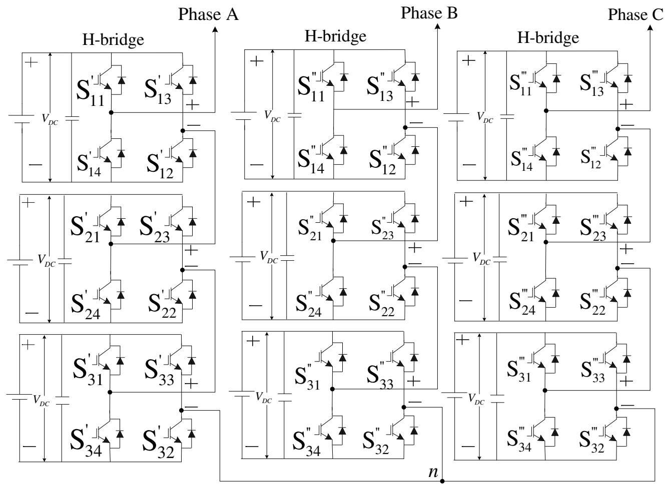

Figure 1. *Circuit diagram of three phase seven level cascaded H-bridge inverter.*

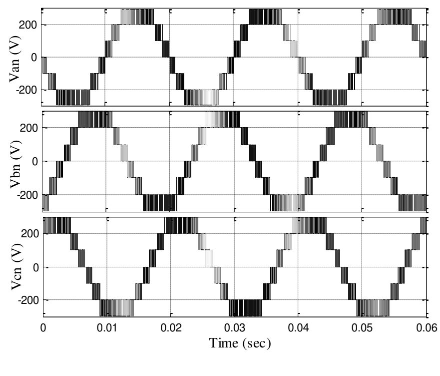

Figure 2. *Phase voltage of three phase seven level inverter.*

Phase voltage and line voltage for three phase seven level inverter are shown in Fig. 2. Switching states of three phase seven level inverter for phase A is described in Table 1. Switching states for phase B and phase C will be same as shown for phase A. Thus, the control of H-bridge configuration becomes simpler and easier due to modularity found in each H-bridge.

Table 1. *Switching table for Phase A*

Voltage Levels	Switching sequence for Phase A											
	S'_{11}	S'_{12}	S'_{13}	S'_{14}	S'_{21}	S'_{22}	S'_{23}	S'_{24}	S'_{31}	S'_{32}	S'_{33}	S'_{34}
+3V	1	1	0	0	1	1	0	0	1	1	0	0
+2V	1	1	0	0	1	1	0	0	1	0	1	0
+V	1	1	0	0	1	0	1	0	1	0	1	0
0	1	0	1	0	1	0	1	0	1	0	1	0
-V	0	0	1	1	1	0	1	0	1	0	1	0
-2V	0	0	1	1	0	0	1	1	1	0	1	0
-3V	0	0	1	1	0	0	1	1	0	0	1	1

- $+3V_{dc}$ is generated across phase A when switches S'_{11} & S'_{12} are ON for first H-bridge, switches S'_{21} & S'_{22} are ON for second H-bridge and switches S'_{31} & S'_{32} are ON for third H-bridge.
- $+2V_{dc}$ is generated across phase A when switch S'_{11} & S'_{12} are ON for first H-bridge, switch S'_{21} & S'_{22} are ON for second H-bridge switch S'_{31} & S'_{33} are ON for third H-bridge.
- $+V_{dc}$ is generated across phase A when switch S'_{11} & S'_{12} are ON for first H-bridge, switch S'_{21} & S'_{23} are ON for second H-bridge, switch S'_{31} & S'_{33} are ON for third H-bridge.
- $0V_{dc}$ is generated across phase A when switch S'_{11} & S'_{13} are ON for first H-bridge, switch S'_{21} & S'_{23} are ON for second H-bridge, switch S'_{31} & S'_{33} are ON for third H-bridge.
- $-V_{dc}$ is generated across phase A when switch S'_{13} & S'_{14} are ON for first H-bridge, switch S'_{21} & S'_{23} are ON for second H-bridge, switch S'_{31} & S'_{33} are ON for third H-bridge.
- $-2V_{dc}$ is generated across phase A when switch S'_{13} & S'_{14} are ON for first H-bridge, switch S'_{23} & S'_{24} are ON for second H-bridge, switch S'_{31} & S'_{33} are ON for third H-bridge.
- $-3V_{dc}$ is generated across phase A when switch S'_{13} & S'_{14} are ON for first H-bridge, switch S'_{23} & S'_{24} are ON for second H-bridge, switch S'_{33} & S'_{34} are ON for third H-bridge.

3. MULTI-CARRIER PWM TECHNIQUE

Carrier based PWM techniques are well established control techniques for multilevel inverters. Recently, various advancements have been done in the area of control techniques so as to obtain the output voltage with lesser THD content. Sinusoidal pulse width modulation (SPWM) among the other PWM techniques is much more popular due to its simpler implementation. Triangular carrier and sawtooth carriers with different PWM schemes i.e. signals i.e. Phase Disposition PWM (PD PWM), Phase Opposition Disposition PWM (POD PWM), Alternate Phase Opposition Disposition PWM (APOD PWM) are used for different arrangement techniques of the carriers [22-26].

3.1. Constant Frequency Based PWM Techniques for Triangular and Sawtooth Carriers

Constant frequency refers that all carriers having the same frequency for a given period of time. Constant frequency arrangement of carriers for PD PWM, POD PWM, APOD PWM with triangular carriers are shown in Fig. 3(a), Fig. 3(b), Fig. 3(c) respectively whereas constant frequency arrangement of carriers for PD PWM, POD PWM, APOD PWM with sawtooth carriers are shown in Fig. 3(d), Fig. 3(e), Fig. 3(f) respectively.

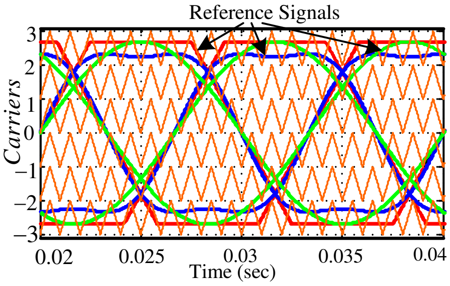

Figure 3(a). *CF-PD PWM*

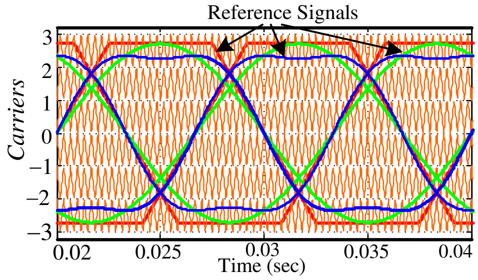

Figure 3(b). *CF-POD PWM*

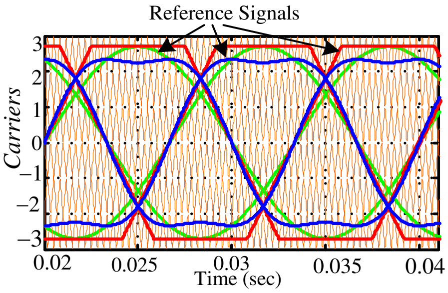

Figure 3(c). *CF-APOD PWM*

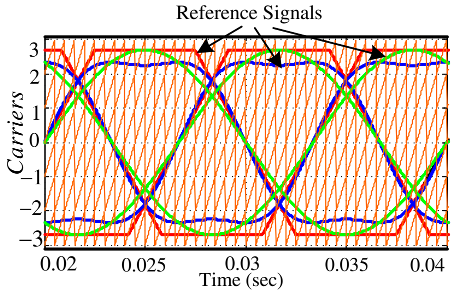

Figure 3(d). *CF-PD PWM*

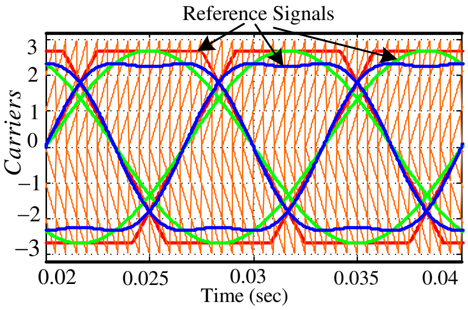

Figure 3(e). *CF-POD PWM*

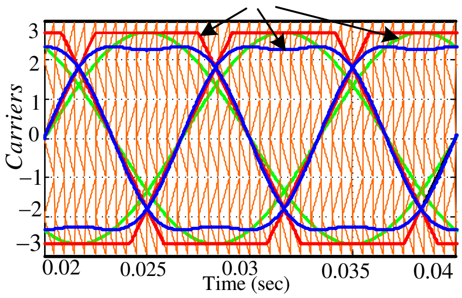

Figure 3(f). *CF-APOD PWM*

3.2. Variable Frequency Based PWM Techniques for Triangular and Sawtooth Carriers

Variable frequency refers that all carriers having the different frequency for a given period of time. Variable frequency arrangement of carriers for PD PWM, POD PWM, APOD PWM with triangular carriers are shown in Fig. 4(a), Fig. 4(b), Fig. 4(c) respectively whereas constant frequency arrangement of carriers for PD-PWM, POD PWM, APOD PWM with sawtooth carriers are shown in Fig. 4(d), Fig. 4(e), Fig. 4(f) respectively.

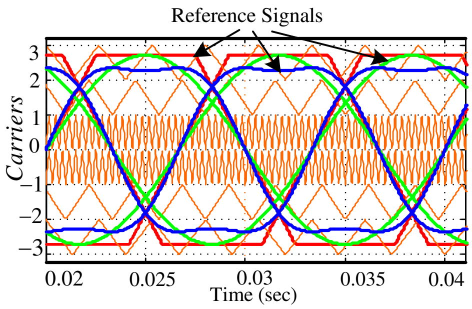

Figure 4(a). *VF-PD PWM*

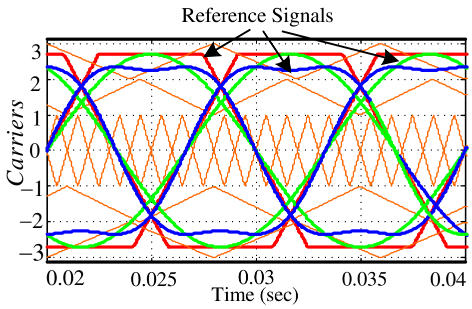

Figure 4(b). *VF-POD PWM*

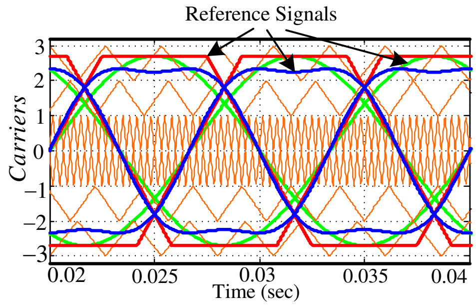

Figure 4(c). *VF-APOD PWM*

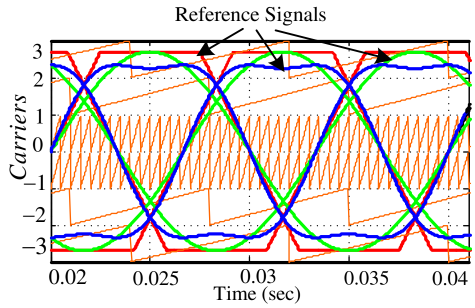

Figure 4(d). *VF-PD PWM*

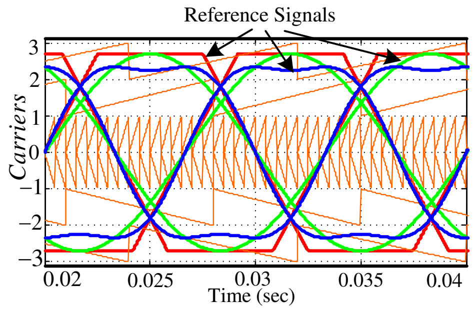

Figure 4(e). *VF-POD PWM*

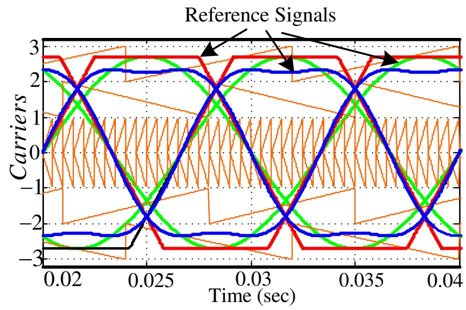

Figure 4(f). *VF-APOD PWM*

3.3. Carrier Overlapping Based PWM Techniques for Triangular and Sawtooth Carriers

Carrier overlapping refers that all carriers having the same frequency for a given period of time but overlapped between two carriers. Carrier overlapping arrangement of carriers for PD PWM, POD PWM, APOD PWM with triangular carriers are shown in Fig. 5(a), Fig. 5(b), Fig. 5(c) respectively whereas carrier overlapping arrangement of carriers for PD PWM, POD PWM, APOD PWM with sawtooth carriers are shown in Fig. 5(d), Fig. 5(e), Fig. 5(f) respectively.

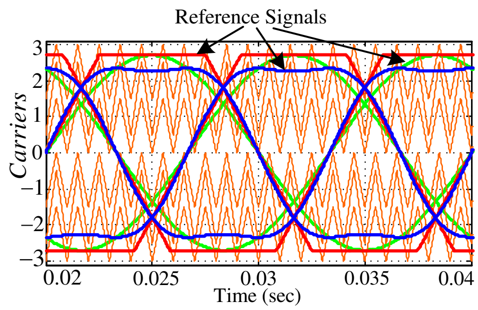

Figure 5(a). *CO-PD PWM*

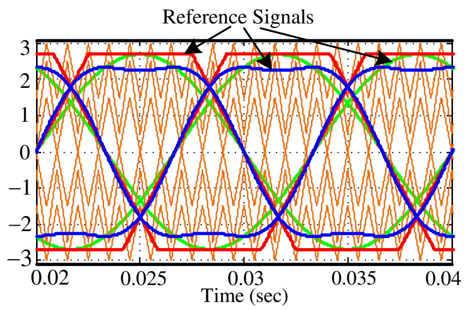

Figure 5(b). *CO-POD PWM*

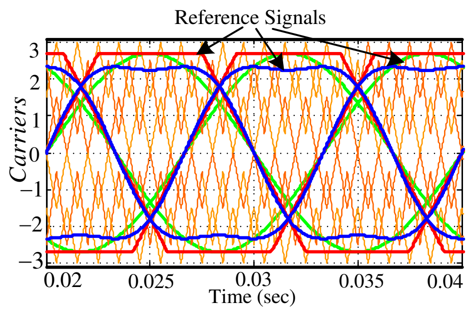

Figure 5(c). *CO-APOD PWM*

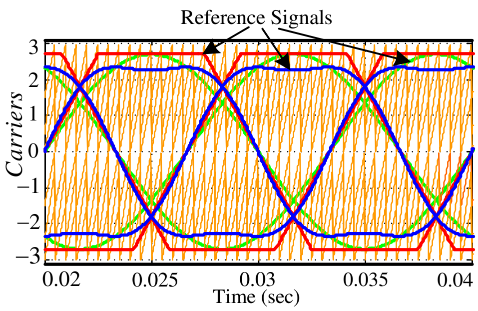

Figure 5(d). *CO-PD PWM*

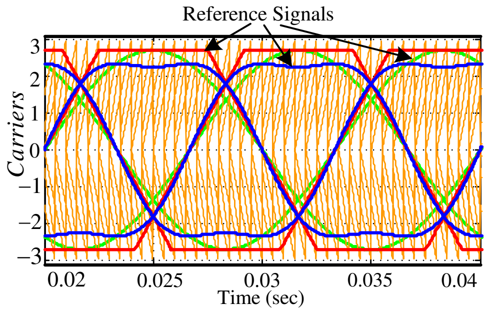

Figure 5(e). *CO-POD PWM*

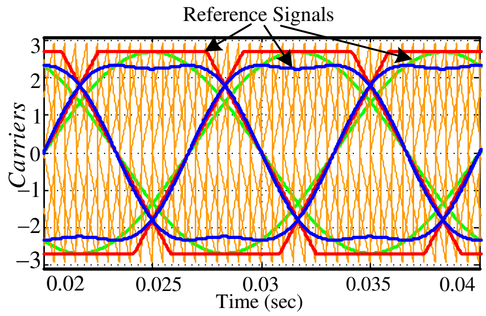

Figure 5(f). *CO-APOD PWM*

4. RESULTS and DISCUSSION

Modeling and simulation of the overall topology has been carried out in MATLAB/Simulink environment at carrier frequency (fc) of 3 kHz. Various charts has been incorporated to compare the THD content for sinusoidal reference with triangular as well as sawtooth carriers as shown in Fig. 6(a) and Fig. 6(b) respectively.

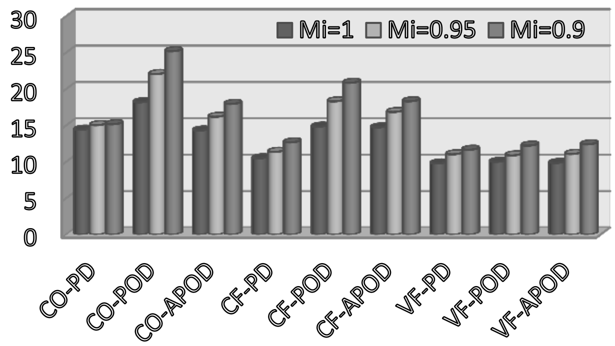

Figure 6(a). *Sine Reference with triangular carrier.*

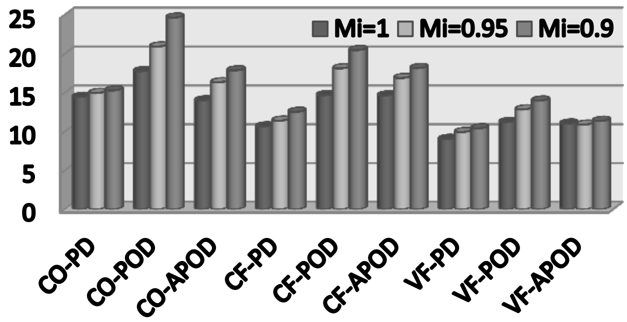

Figure 6(b). *Sine Reference with sawtooth carrier.*

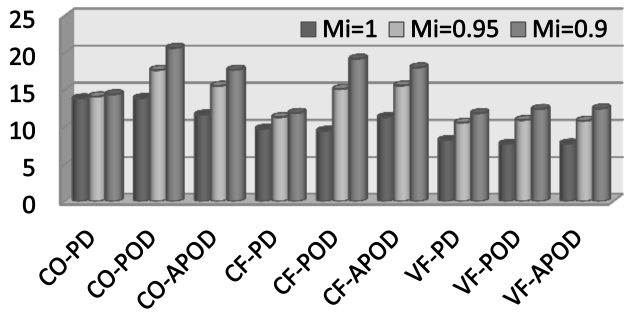

Figure 6(c). *Trapezoidal Reference with triangular carrier.*

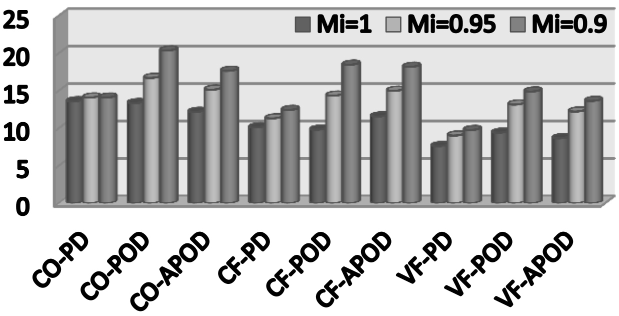

Figure 6(d). *Trapezoidal Reference with sawtooth carrier.*

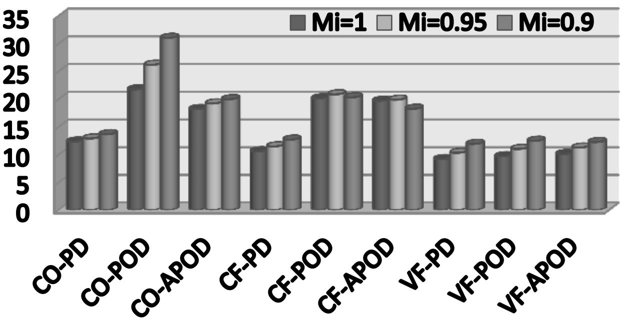

Figure 6(e). *Sine Third Harmonic Reference with triangular carrier.*

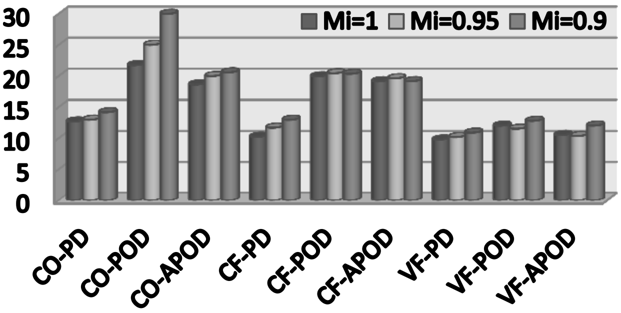

Figure 6(f). *Sine Third Harmonic Reference with sawtooth carrier*

Figure 6. *%THD content at different modulation index (mi=1, 0.95 and 0.9) (X axis : Different PWM Techniques at different modulation index; Y axis : %THD content).*

The chart shows the %THD content at different modulation index as mentioned. From Fig. 6(a), it has been observed that CO-PD PWM among the carrier overlapping (CO) arrangements of carriers gives better result, CF-PD PWM among constant frequency (CF) arrangements of carriers gives better result and VF-PDPWM among variable frequency (VF) arrangements of carriers gives better result whereas it can be noticed that all the variable frequency (VF) arrangements of carriers provides better result compared to the other carrier arrangement techniques i.e. CF & CO. From Fig. 6(b), it is clearly understood that performance of VF-POD still better compared to CO-POD & CF-POD PWM. Variable frequency (VF) arrangements of carriers i.e. VF-PD PWM & VF-APOD PWM provides better result compared to the other carrier arrangement techniques i.e. CF & CO. Taking in account the trapezoidal reference with triangular and sawtooth carriers, it can be concluded from Fig. 6(c) that VF based carrier arrangements gives much lesser THD compared to the other carrier arrangements i.e. CO & CF at different modulation index. Among CO, CF & VF arrangements of the carrier, VF-PD, VF-POD, VF-APOD PWM stands with the best result at any modulation index as shown in Fig. 6(d). Similarly, %THD content in third harmonic injected sinusoidal references with triangular and sawtooth carriers for different arrangement of carriers are shown in Fig. 6(e) & Fig. 6(f) respectively. It has been noticed that VF carrier arrangements in all different types of PWM such as PD, POD & APOD stands the best. It can be said that the %THD results the best for triangular carriers compared to the sawtooth carriers.

Table 2(a). %THD content for sinusoidal reference signal at modulation index (mi=1)

%THD of phase voltage (VPh) and line voltage (VL) for sinusoidal reference signal				
	Sawtooth Carrier		Triangular Carrier	
	%THD for VPh	%THD for VL	%THD for VPh	%THD for VL
CF-PD PWM	17.95	10.66	18.23	10.48
CF-POD PWM	17.53	14.69	18.24	14.83
CF-APOD PWM	17.66	14.65	18.01	14.72
CO-PD PWM	24.88	15.29	25.09	15.16
CO-POD PWM	24.29	17.77	24.83	18.18
CO-APOD PWM	17.24	14.01	17.71	14.30
VF-PD PWM	12.49	9.05	11.13	9.50
VF-POD PWM	12.72	11.23	11.76	10.00
VF-APOD PWM	12.08	11.03	12.01	9.84

Table 2(b). *%THD content for third harmonic sinusoidal reference signal at modulation index (mi=1)*

%THD of phase voltage (VPh) and line voltage (VL) for third harmonic injected sinusoidal reference signal				
	Sawtooth Carrier		Triangular Carrier	
	%THD for VPh	%THD for VL	%THD for VPh	%THD for VL
CF-PD PWM	27.29	10.22	27.23	10.59
CF-POD PWM	27.18	19.94	27.04	20.14
CF-APOD PWM	27.00	19.15	27.13	19.69
CO-PD PWM	29.47	12.69	29.33	12.34
CO-POD PWM	29.06	21.75	29.62	21.76
CO-APOD PWM	24.59	18.63	24.99	18.19
VF-PD PWM	21.82	9.79	18.41	9.17
VF-POD PWM	17.24	12.01	20.15	9.69
VF-APOD PWM	17.66	10.51	19.78	10.10

Table 2(c). %THD content for sinusoidal reference signal at modulation index (mi=1)

%THD of phase voltage (VPh) and line voltage (VL) for trapezoidal reference signal				
	Sawtooth Carrier		Triangular Carrier	
	%THD for VPh	%THD for VL	%THD for VPh	%THD for VL
CF-PD PWM	17.86	10.12	16.70	9.78
CF-POD PWM	17.34	9.81	16.67	9.50
CF-APOD PWM	17.22	11.58	16.35	11.34
CO-PD PWM	22.11	13.60	21.63	13.87
CO-POD PWM	21.72	13.35	21.48	13.91
CO-APOD PWM	17.45	12.19	17.47	11.69
VF-PD PWM	15.36	7.62	13.75	8.26
VF-POD PWM	14.45	9.41	14.42	7.74
VF-APOD PWM	41.70	8.68	14.21	7.79

Table 3(a). *%THD content for triangular carrier*

%THD for different reference signal for triangular carrier			
	Sinusoidal Reference Signal	Trapezoidal Reference Signal	Third Harmonic Injected Sinusoidal Reference Signal
CO-PD PWM	15.16	13.87	12.34
CF-PD PWM	10.48	9.78	10.59
VF-PD PWM	9.77	8.26	9.17
CO-POD PWM	18.18	13.91	21.76
CF-POD PWM	14.83	9.50	20.14
VF-POD PWM	10.00	7.74	9.69
CO-APOD PWM	14.30	11.69	18.19
CF-APOD PWM	14.72	11.34	19.69
VF-APOD PWM	9.84	7.79	10.10

Table 3(b). *%THD content for sawtooth carrier*

%THD for Different Reference Signal for Sawtooth Carrier			
	Sinusoidal Reference Signal	Trapezoidal Reference Signal	Third Harmonic Injected Sinusoidal Reference Signal
CO-PD PWM	15.29	13.60	12.69
CF-PD PWM	10.66	10.12	10.22
VF-PD PWM	9.05	7.62	9.79
CO-POD PWM	17.77	13.35	21.75
CF-POD PWM	14.69	9.81	19.94
VF-POD PWM	11.23	9.41	12.01
CO-APOD PWM	14.01	12.19	18.63
CF-APOD PWM	14.65	11.58	19.15
VF-APOD PWM	11.03	8.68	10.51

Table. 2(a), Table. 2(b), Table. 2(c) presents %THD content in phase voltage and line voltage for sinusoidal reference signal, third harmonic injected sinusoidal reference signal and trapezoidal reference signal respectively at modulation index (mi=1). %THD is measured for CF, CO & VF arrangements of carriers with PD-PWM, POD-PWM, APOD-PWM. Sinusoidal reference signal based CF-PD PWM, CO-APOD PWM & VF-PD PWM gives lesser %THD content for both sawtooth and triangular carriers. It can be said from Table. 2(a) that CO based APOD PWM whereas CF & VF based POD arrangement generates the lesser %THD content for line voltage while considering sinusoidal as the reference signal. Third harmonic injected sinusoidal reference signal based CF-PD PWM, CO-PD PWM & VF-PD PWM gives lesser %THD content for both sawtooth and triangular carriers. It can be concluded from Table. 2(b) that CO based PD PWM whereas CF & VF based PD arrangement generates the lesser %THD content for line voltage while considering third harmonic injected sinusoidal as the reference signal. Trapezoidal reference signal based CF-POD PWM, CO-APOD PWM & VF-PD PWM gives lesser %THD content. CF based POD PWM whereas CO based APOD & VF based PD arrangement generates the lesser %THD content for line voltage while considering trapezoidal as the reference signal as shown in Table 2(c). Based on sawtooth and triangular carries, it has been noticed while considering the %THD content from Table 3(a) & 3(b) that trapezoidal reference signal gives better results than the any other references. Trapezoidal reference with sawtooth carriers gives better output in respect to THD content compared to the sawtooth carriers.

5. CONCLUSION

Increasing trends in multilevel inverter for the various industrial applications enhanced the need of reduction in %THD content so as to restrict the current harmonics being generated by non-sinusoidal output voltage.

This work contains the analysis of %THD for various arrangements of carriers i.e. CO, CF & VF with various schemes of SPWM control strategies i.e. PD, POD, & APOD for both triangular and sawtooth carriers at different modulation index. Various aspect of %THD content has been compared and included as chart as well in tabular form. The result indicates that the VF based techniques gives better THD compared to any other references either with sawtooth or triangular carrier. Thus, it can be concluded that the appropriate PWM control strategies to be used depending on performance of the required application.

CONFLICT OF INTEREST

No conflict of interest was declared by the authors.

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