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NEW VARIABLE AMPLITUDE CARRIER OVERLAPPING PWM METHODS FOR THREE PHASE FIVE LEVEL CASCADED INVERTER

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ABSTRACT

This paper presents the comparison of various Carrier Overlapping Pulse Width Modulation (COPWM) Strategies for the chosen three phase Cascaded Multi Level Inverter (CMLI). Various new schemes adopting the constant switching frequency and also variable switching frequency multicarrier control freedom degree combination concepts are developed and simulated for the chosen three phase CMLI. The three phase CMLI, is controlled in this paper with Sinusoidal PWM (SPWM) reference along with Carrier Overlapping (CO) techniques and simulation is performed using MATLAB-SIMULINK. The variation of fundamental RMS output voltage and total harmonic distortion is observed for various carrier overlapping techniques. Among the various equal amplitude carrier overlapping techniques such as COPWM-1, COPWM-2, COPWM-3, and COPWM-4, it is observed that COPWM-3 provides less Total Harmonic Distortion (THD) and COPWM-4 provides relatively higher RMS voltage. Among the various Variable Amplitude COPWM (VACOPWM) techniques such as VACOPWM-1, VACOPWM-2, VACOPWM-3, and VACOPWM-4, it is inferred that VACOPWM-3 provides less THD and VACOPWM-2 and VACOPWM-3 provide higher RMS voltage. It also found that VACOPWM strategies perform better than corresponding COPWM strategies.

Keywords: *VACOPWM-1, VACOPWM-2, VACOPWM-3, VACOPWM-4, THD, CF*

1. INTRODUCTION

Multi Level Inverter (MLI) is a power electronic system that produces a desired sinusoidal output voltage from several levels of DC input voltages. Compared with two level voltage source inverter, multi level inverter normally provides output voltage with less Total Harmonic Distortion (THD), lower voltage stress of devices, lower electromagnetic interference, low level of high frequency noise, higher RMS voltage and lower common-mode voltage. The function of the inverter is to change a DC input voltage to a near sinusoidal output voltage of desired magnitude and frequency. So, it is recently used in medium high voltage and high power applications. Jose Rodríguez et al [1] made a survey on topologies, controls and applications of multilevel inverters. Corzine et al [2] developed the control of cascaded multilevel inverters. Pandey et al [3] made a detailed review of multilevel power converters. Yan Deng et al [4] presented a survey of multilevel PWM methods based on control freedom degrees combination. Geun Song et al [5] carried out survey on cascaded multilevel inverter employing three-phase transformers and single DC input. Zhou and Smedley [6] performed a reliability comparison of multilevel inverters for motor drives. Patangia and Gregory [7] found a new class of optimal multilevel inverter based on sectionalized PWM. Chenchen and Yondong [8] made a study on topologies of multilevel converters and study of two novel topologies. Konstantinou and Agelidis [9] evaluated performance of half-bridge cascaded multilevel converters operated with multicarrier sinusoidal PWM techniques. Anshuman Shukla et al [10] described hysteresis modulation of multilevel inverters. Behzad Vafakhah et al [11] proposed multicarrier interleaved PWM strategies for a five level inverter using a three phase coupled inductor. Balamurugan et al [12] have made a comparative study on carrier overlapping PWM strategies for three phase MLI. Batschauer et al [13] developed a three-phase hybrid multilevel inverter based on half-bridge modules. Suresh and Panda

[14] carried out research on cascaded multilevel inverter by employing three phase transformers.

2. MULTILEVEL INVERTER

MLI is used for obtaining a near sinusoidal signal (AC) from DC input source. As it is simple to implement and eliminate the number of transformers, minimizes the filter requirements and improves the harmonic quality of the output voltage, MLI is extensively used in compressors, synchronous motors, converters and power generation plants. MLI based DC-AC converter has many advantageous features over the conventional PWM inverter; so it is becoming very attractive in electronic power conversion system. When used as inverter, MLI offers better output waveform in comparison with two level PWM inverter and if used as active rectifiers, they allow accurate power factor correction and better approximation of sinusoidal currents. Among many other conventional configurations such as Diode Clamped Multi Level Inverter (DCMLI), Flying Capacitor Multi Level Inverter (FCMLI), it is observed that Cascaded Multi Level Inverter (CMLI) provides high performance with less THD and uses less number of power electronic components. Cascaded multi level inverter is being used popularly, since it can achieve a high range of voltage and power and it has several advantages compared with other conventional inverters such as low THD that eliminate the need of output filters, reduced common-mode and derivative voltages (dv/dt) which can reduce motor insulation, damage and jerks in torque. Three phase CMLI consists of series connection of single-phase H-bridge cells with several separate DC sources. Among the basic MLI topologies, cascaded H-bridge is preferred by its modular structure and linear relationship between the number of inverter elements and levels. But the demand is that large number of DC sources is needed. The fixed DC input voltage which is not controllable can be modified into variable output voltage by varying the gain of the inverter which can be achieved by Pulse Width Modulation (PWM) strategies.

Fig. 1 shows a configuration of the three phase five level cascaded multilevel inverter. Cascaded multilevel inverter consists of a series of H bridge inverter units. The general function of this inverter is to produce a desired voltage from several Separate DC Sources (SDCS). The load voltage is equal to the sum of the output voltage of the respective modules that are connected in series. The number of modules (M) that is equal to the number of DC sources required depends on the total number of positive, negative and zero levels (m) of the CMLI. It is usually assumed that m (number of levels) is odd as this would give an integer valued M (number of modules). In this work, load voltage consists of five levels which include $+2V_{dc}$, $+V_{dc}$, 0, $-V_{dc}$ and $-2V_{dc}$ and the number of modules required is 2. The following equation gives the relation between M and m.

$$M = \frac{m-1}{2}$$

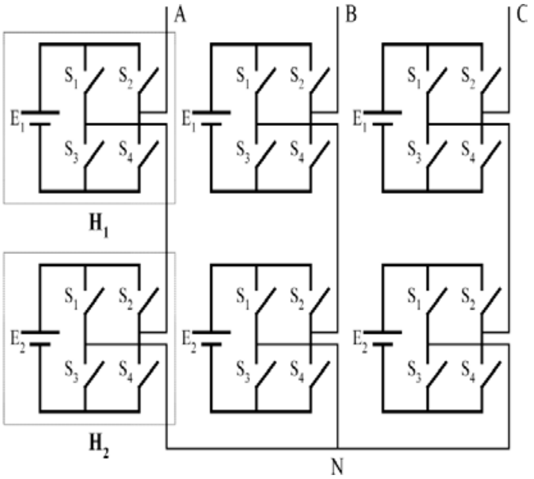

Figure 1: Three Phase Five Level Cascaded Multilevel Inverter

The gate signals for chosen five level cascaded inverter are simulated using MATLAB-SIMULINK. The gate signal generator model developed is tested for various values of modulation index m_a and for various PWM strategies. The simulation results presented in this work are compared and evaluated for finding the better technique.

3. MODULATION STRATEGIES

In this paper, sinusoidal reference with various overlapping triangular carriers are chosen to produce the desired output. The function of any inverter is to change a DC input voltage to a near AC output voltage of desired magnitude and frequency which can be achieved by various modulation strategies. The number of triangular carriers needed for m level inverter is m-1. Eight different modulation strategies are taken for study to provide increased output voltage and also reduced THD by controlling the on and off time of PWM signal. It is generally recognized that, increasing the switching frequency of the PWM pattern results in reducing lower frequency harmonic waveforms of practical inverters which are non-sinusoidal and contain harmonics, so analysis is performed in order to choose the proper PWM strategy.

This paper focuses on eight different COPWM strategies that utilize the Control Degree Freedom (CFD) combination of vertical offsets among triangular carriers. They are: COPWM-1, VACOPWM-1, COPWM-2, VACOPWM-2 COPWM-3, VACOPWM-3, COPWM-4, and VACOPWM-4. The chosen eight different modulation strategies are simulated in this work and the comparisons are made among them to choose the better technique which will be efficient and provides the output with improved power quality. Carriers are chosen above and below the zero reference line with same amplitude of A_c =1.6 in case of the three basic COPWM techniques and the other four are VACOPWM technique in which the amplitude of first carrier is chosen as 50% of the basic COPWM method and amplitude of the second carrier is 125% of the basic COPWM strategy and the same procedure is repeated below the zero reference line.

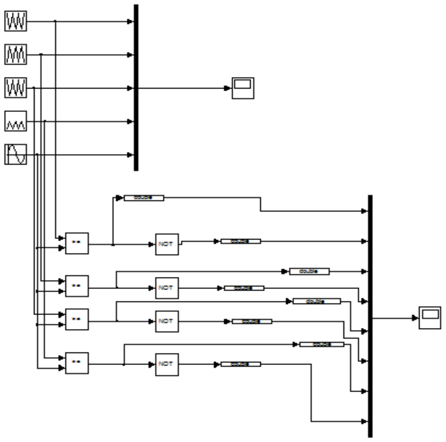

Figure 2: A Sample SIMULINK Model Developed For Chosen Three Phase Multilevel Inverter For VACOPWM-1 Technique

3.1 COPWM-1 Strategy

In this method all carriers have the same frequency, same amplitude and same phase. Carriers needed for m level inverter is m-1 and hence four triangular carriers with overlapping among them and one sine reference is chosen for the five level inverter under study. All carriers selected above and below the zero reference is in same phase and the amplitude of each carrier is chosen as A_c= 1.6 and assumed to be equal in magnitude and overlapping amplitude will be $A_c/2=0.8$. Since all carriers are in same phase with equal amplitude and overlapping among them, it is named as Carrier Overlapping Pulse Width Modulation -1 (COPWM-1) strategy. The carrier arrangement for this strategy is shown in Fig.3.

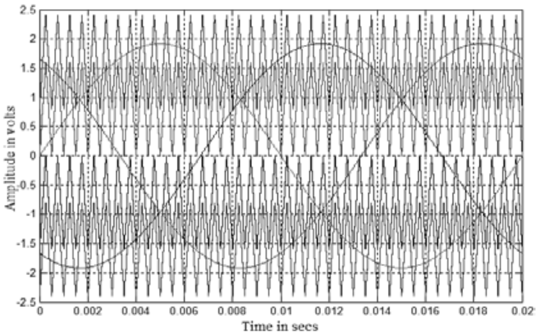

Figure 3: Modulating and carrier waveforms for COPWM-1 strategy (m_a = 0.8 and m_f = 40)

3.2 VACOPWM-1 Strategy

In this method all carriers have the same frequency, same phase and varying amplitude. So it is named as Variable Amplitude Carrier Overlapping Pulse Width Modulation-1 (VACOPWM-1) strategy. Since all carriers are selected with the same phase, this method is similar to conventional Phase Disposition(PD) strategy except with varying amplitude and carrier overlapping of $A_c/4=0.4$, where $A_{c=}1.6$ is the carrier amplitude. It is found from literature that this PWM provides lower total harmonic distortion and relatively higher fundamental RMS voltage while comparing to above discussed COPWM-1 technique. The carrier arrangement for this strategy is shown in Fig.4.

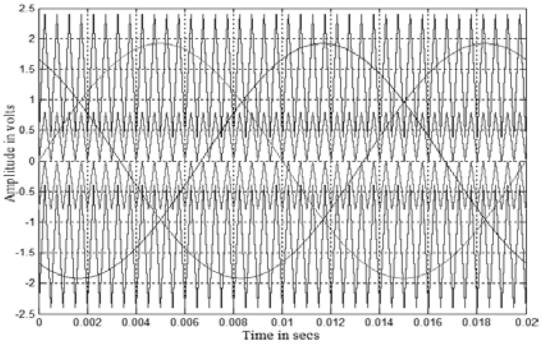

Figure 4: Modulating and carrier waveforms for VACOPWM-1 strategy (m_a = 0.8 and m_f = 40)

3.3 COPWM-2 Strategy

Carrier arrangement for COPWM-2 strategy is shown in Fig.5. Four carriers which are generated for five level inverter are divided into two groups according to the positive and negative average levels. . This scheme is similar to the conventional Phase Opposition Disposition (POD) PWM strategy such that the two groups are opposite in phase with each other with overlapping amplitude of $A_c/2=0.8$. So it is named as Carrier Overlapping Pulse Width Modulation-2 (COPWM-2) technique. This COPWM-2 is same as COPWM-1 strategy but is having the carriers above the zero line of reference voltage out of phase with those of below the zero reference line by 180 degrees such that each carrier amplitude is chosen as 1.6 and overlapping is 0.8.

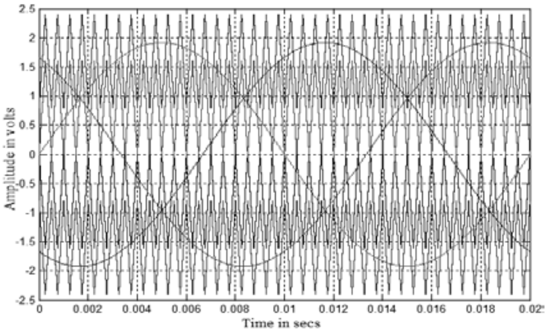

Figure 5: Modulating and carrier waveforms for COPWM-2 strategy (m_a = 0.8 and m_f = 40)

3.4 VACOPWM-2 Strategy

The VACOPWM-2 is same as COPWM-2 strategy but with varying amplitude and the carriers above the zero reference line is out of phase with those of below the line by 180 degrees and overlapping amplitude of carrier is chosen as $A_c/4=0.4$.

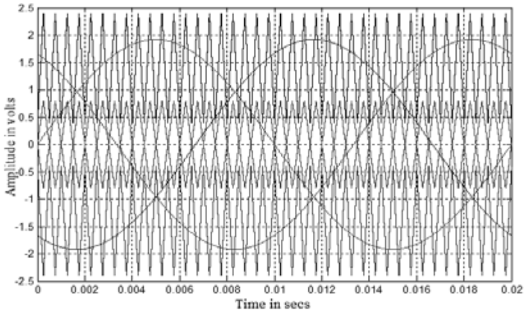

Figure 6: Modulating and carrier waveforms for VACOPWM-2 strategy (m_a = 0.8 and m_f = 40)

Carrier arrangement for VACOPWM-2 is shown in Fig.6. Since carriers are divided into two average levels according to the positive and negative groups, above and below the zero reference line with varying amplitude such that the two groups are opposite in phase with each other with an overlapping amplitude of 0.4, it is named as Variable Amplitude Carrier Overlapping Pulse Width Modulation (VACOPWM-2) strategy.

3.5 COPWM-3 Strategy

In this strategy, carriers seem to invert their phase in turns from previous one and the same procedure is repeated below the zero average levels, with overlapping amplitude of $A_c/2$= 0.8. This method is similar to conventional Alternate Phase Opposition Disposition (APOD) PWM technique where there is no overlapping among the carriers. This pattern is named as Carrier Overlapping Pulse Width Modulation-3 strategy. Carrier arrangement for this strategy is shown in Fig.7.

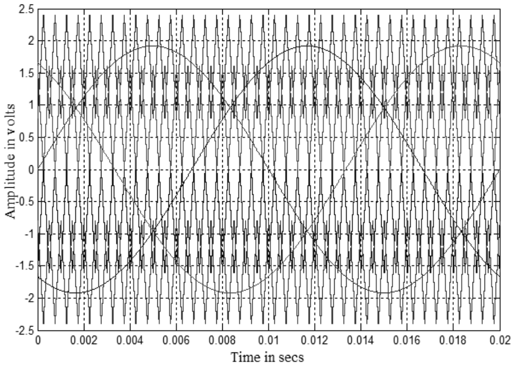

Figure 7: Modulating and carrier waveforms for COPWM-3 strategy (m_a = 0.8 and m_f = 40)

3.6 VACOPWM-3 Strategy

Carrier arrangement for this strategy is shown in Fig.8. In this pattern, carriers invert their phase in turn from the previous one with same frequency and varying amplitude with overlapping of $A_c/4=0.4$. So it is named as Variable Amplitude Carrier Overlapping Pulse Width Modulation (VACOPWM-3) strategy.

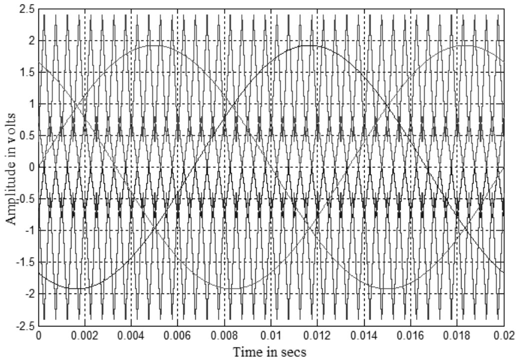

Figure 8: Modulating and carrier waveforms for VACOPWM-3 strategy(m_a = 0.8 and m_f = 40)

3.7 COPWM-4 Strategy

Switching pattern is not equal in COPWM-1 strategy. In order to balance the fluctuations in switching pattern for all the switches, variable frequency carrier overlapping PWM scheme is used as illustrated in Fig.9 in which carrier frequency of the intermediate switches is properly increased to balance the number of switching for all the bridges. All carriers are in same phase, same amplitude and varying frequency with overlapping amplitude of 0.4. Hence it is named as Carrier Overlapping Pulse Width Modulation-4 (COPWM-4) strategy.

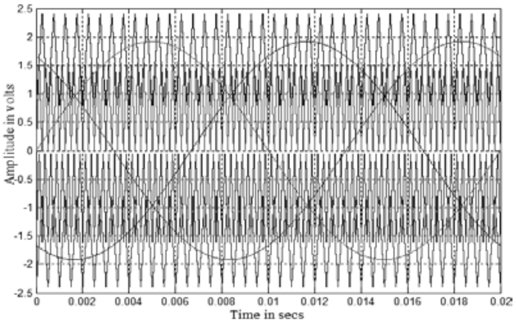

Figure 9: Modulating and carrier waveforms for COPWM-4 strategy(m_a = 0.8 and m_f = 40 for lower and upper switches and m_a = 0.8 and m_f = 80 for intermediate switches)

3.8 VACOPWM-4 Strategy

In order to equalize the switching pattern for all the switches, variable amplitude carrier overlapping variable frequency PWM is introduced as illustrated in Fig.10 in which the carrier frequency of the intermediate switches is properly increased to balance the switching pattern for all the bridges. All carriers are in same phase, varying amplitude with overlapping of $A_c/2$= 0.8. So it is named as Variable Amplitude Carrier Overlapping Pulse Width Modulation-4 (VACOPWM-4) strategy.

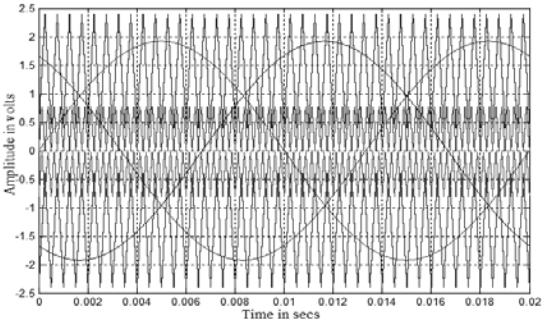

Figure 10: Modulating and carrier waveforms for VACOPWM-4 strategy (m_a = 0.8 and m_f = 40 for lower and upper switches and m_a = 0.8 and m_f = 80 for intermediate switches)

4. SIMULATION RESULTS

Simulation studies are performed by using MATLAB-SIMULINK to verify and analyze the proposed PWM strategies for the chosen three phase cascaded five level inverter for various values of m_a ranging from 0.6 – 1 and corresponding %THD values are measured using FFT block and they are shown in Table I. THD which is a measure of closeness in shape between a waveform and its fundamental component Crest Factor (CF) indicative of peak value, Form Factor (FF) representing the shape of output wave and Distortion Factor (DF) which is a measure of effectiveness in reducing unwanted noise and harmonics are measured from the FFT plots. The following parameters are used for the simulation results V_{dc}=440V, f_c=2000Hz, f_m=50Hz and R=100Ω. Table II displays the V_{RMS} (fundamental) output of inverter for the same modulation indices. Table III provides the form factor for different modulation indices which are calculated using RMS voltage and DC component from FFT plots. Table IV portrays crest factor values which are measured using peak voltage and RMS voltage from FFT plots. Table V presents the distortion factor for different modulation indices. Figs.11-18 show the simulated output voltages of chosen CMLI and the corresponding FFT plots with different strategies but only for one sample value of m_a = 0.8 , m_f = 40 and m_f=80 only for the intermediate switches in COPWM-4 and VACOPWM-4. Fig.11 shows the five level output voltage generated by COPWM-1 strategy and its FFT plot is shown in Fig.19. It is observed that the COPWM-1 strategy produces significant 36th and 40th harmonic energy. Fig.12 shows the five level output voltage generated by VACOWM-1 strategy and from of Fig.20, it is observed that the VACOPWM-1 strategy produces significant 3rd, and 40th harmonic energy. Fig.13 shows the five level output voltage generated by COPWM-2 strategy and its FFT plot is shown in Fig.21. It is observed that the COPWM-2 strategy produces significant 3rd, 5th, 37th and 39th harmonic energy. Fig.14 shows five level output voltage generated by VACOPWM-2 strategy and from Fig.22 it is observed that the VACOPWM-2 produces significant 3rd, 5th, 37th and 39th harmonic energy. Fig.15 shows the five level output voltage generated by COPWM-3 strategy and its FFT plot is shown in Fig.23. It is observed that COPWM-3 strategy produces significant 3rd, 5th, 35th, 37th and 39th harmonic energy. Fig.16 shows the five level output voltage generated by VACOPWM-3 strategy and its FFT plot is shown in Fig.24. It is observed that VACOPWM-3 strategy produces significant 3rd, 5th, 29th , 31st , 33rd , 35th and 39th harmonic energy. Fig.17. shows the five level output voltage generated by COPWM-4 strategy and its FFT plot is shown in Fig.25. It is observed that the COPWM-4 strategy produces significant 3rd, 5th, 36th, 38th and 40th harmonic energy. Fig.18 shows the five level output voltage generated by VACOPWM-4 strategy and its FFT plot is shown in Fig.26. It is observed that the VACOPWM-4 strategy produces significant 3rd, 36th, 38th and 40th harmonic energy. Among the various equal amplitude carrier overlapping techniques such as COPWM-1, COPWM-2, COPWM-3, and COPWM-4, it is observed that COPWM-3 provides less Total Harmonic Distortion (THD) and COPWM-4 provides relatively higher RMS voltage. Among the various Variable Amplitude COPWM (VACOPWM) techniques such as VACOPWM-1, VACOPWM-2, VACOPWM-3, and VACOPWM-4, it is inferred that VACOPWM-3 provides less THD and VACOPWM-2 and VACOPWM-3 provide higher RMS voltage. It also found that VACOPWM strategies perform better than corresponding COPWM strategies.

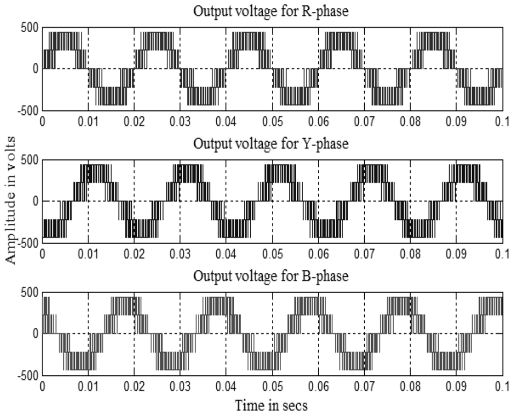

Figure 11: Simulated output voltage generated by COPWM-1 technique for R-load

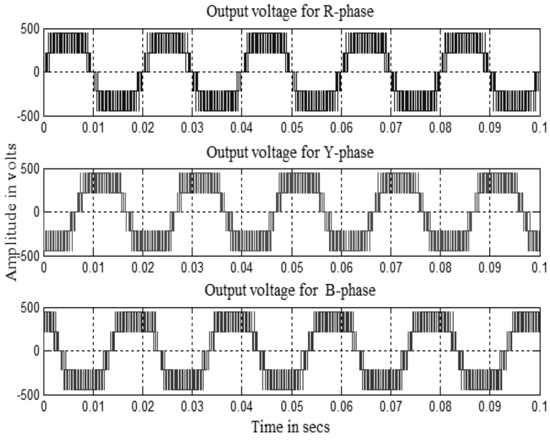

Figure 12: Simulated output voltage generated by VACOPWM-1 technique for R-load

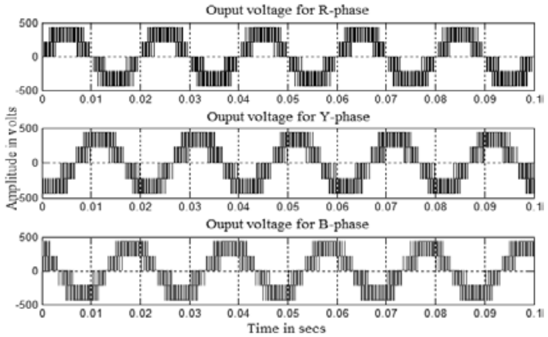

Figure 13: Simulated output voltage generated by COPWM-2 technique for R-load

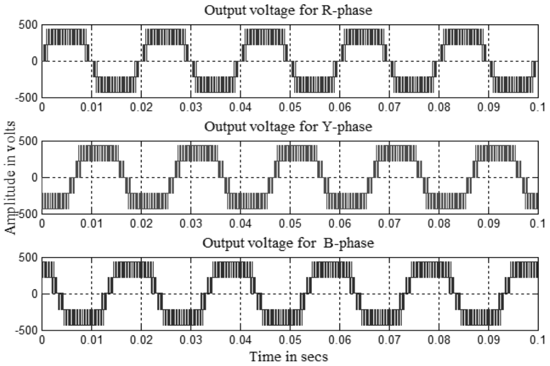

Figure 14: Simulated output voltage generated by VACOPWM-2 technique for R-load

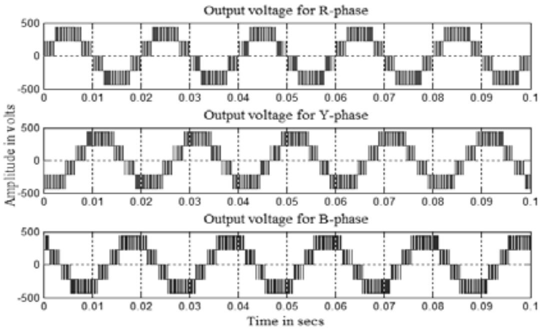

Figure 15: Simulated output voltage generated by COPWM-3 technique for R-load

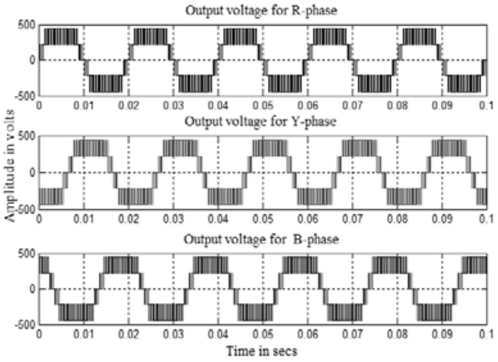

Figure 16: Simulated output voltage generated by VACOPWM-3 technique for R-load

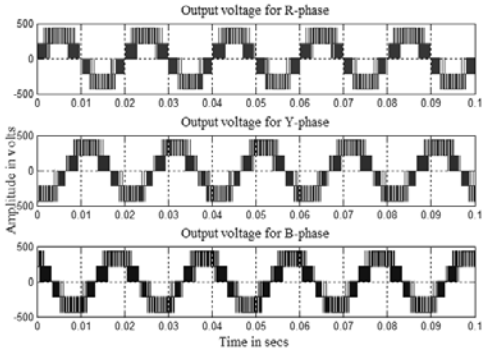

Figure 17: Simulated output voltage generated by COPWM-4 technique for R-load

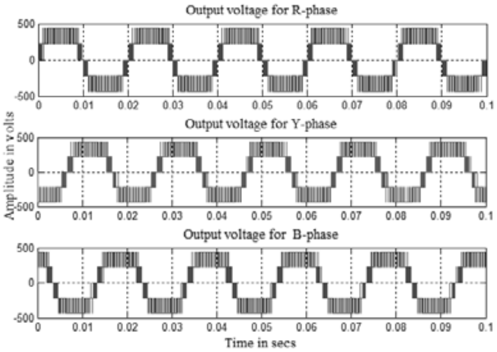

Figure 18: Simulated output voltage generated by VACOPWM-4 technique for R-load

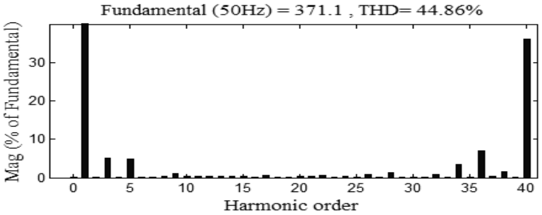

Figure 19: FFT spectrum for COPWM-1 technique

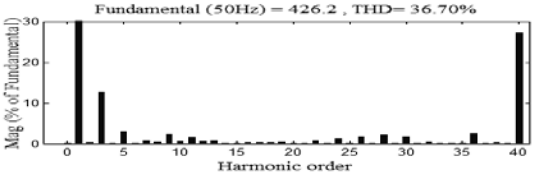

Figure 20: FFT spectrum for VACOPWM-1 technique

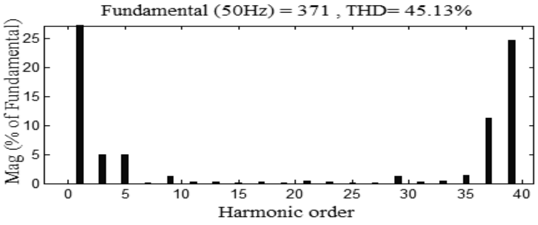

Figure 21: FFT spectrum for COPWM-2 technique

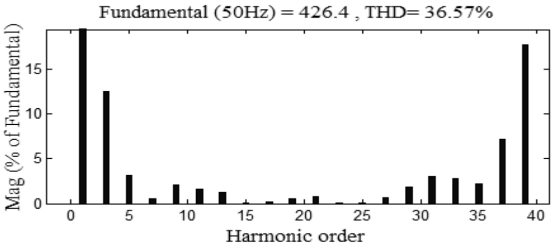

Figure 22: FFT spectrum for VACOPWM-2 technique

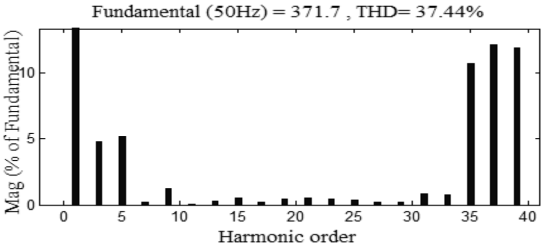

Figure 23: FFT spectrum for COPWM-3 technique

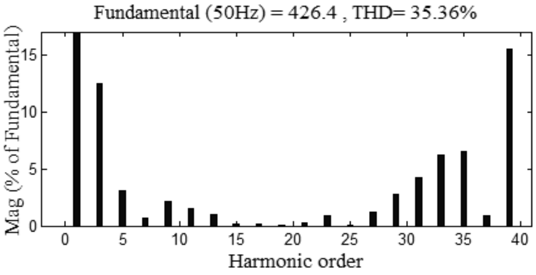

Figure 24: FFT spectrum for VACOPWM-3 technique

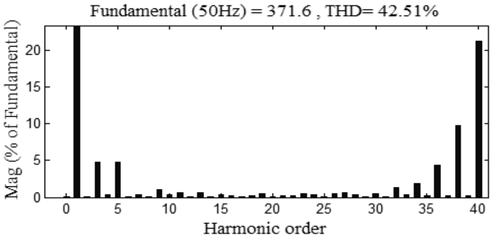

Figure 25: FFT spectrum for COPWM-4 technique

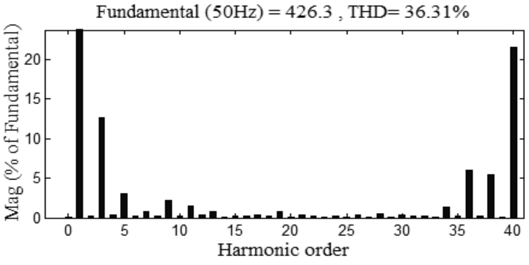

Figure 26: FFT spectrum for VACOPWM-4 technique

Table 1: % THD of Output Voltage of Chosen CMLI for various Values of Modulating Indices

% THD	**m_a**				
	1.0	**0.9**	**0.8**	**0.7**	**0.6**
CO-1	31.67	38.11	44.86	53.3	69.72
VACO-1	29.17	33.22	36.70	39.4	42.21
CO-2	31.58	37.97	45.13	52.9	70.08
VACO-2	28.71	32.78	36.57	39.3	42.12
CO-3	26.89	32.15	37.44	42.4	48.57
VACO-3	27.93	31.40	35.36	37.7	39.83
CO-4	30.26	36.23	42.51	50.1	63.14
VACO-4	28.67	32.81	36.31	38.6	41.38

Table 2: V_{rms} (Fundamental) of Output Voltage of Chosen CMLI for various Values of Modulating Indices

V_{rms}	**m_a**				
	1.0	**0.9**	**0.8**	**0.7**	**0.6**
CO-1	318.1	291.2	262.4	229.9	185.7
VACO-1	340.7	321.5	301.4	281.5	259.8
CO-2	318.1	291.5	262.3	230.1	184.7
VACO-2	340.9	322.2	301.5	281.3	259.9
CO-3	317.5	291.5	262.8	229.6	185.9
VACO-3	341.1	321.7	301.5	281.2	259.6
CO-4	318	291.7	262.8	229.5	186
VACO-4	340.7	321.4	301.5	281.6	259.7

Table 3: Form Factor of Output Voltage of Chosen CMLI for various Values of Modulating Indices

FF	**m_a**				
	1.0	**0.9**	**0.8**	**0.7**	**0.6**
CO-1	INF	9706	8746	7663.3	546.1
VACO-1	1892	16075	3767	3518	8660
CO-2	INF	INF	INF	INF	INF
VACO-2	INF	INF	INF	INF	INF
CO-3	INF	INF	INF	INF	INF
VACO-3	INF	INF	INF	INF	INF
CO-4	INF	3646	2920	2295	2325
VACO-4	6814	16070	2319	2011	8656

Table 4: Crest Factor of Output Voltage of Chosen CMLI for various Values of Modulating Indices

CF	**m_a**				
	1.0	**0.9**	**0.8**	**0.7**	**0.6**
CO-1	1.414	1.414	1.41	1.41	1.414
VACO-1	1.414	1.414	1.41	1.41	1.414
CO-2	1.414	1.41	1.41	1.41	1.414
VACO-2	1.414	1.414	1.41	1.41	1.414
CO-3	1.414	1.414	1.41	1.41	1.414
VACO-3	1.413	1.414	1.41	1.41	1.414
CO-4	1.414	1.414	1.41	1.41	1.413
VACO-4	1.414	1.414	1.41	1.41	1.414

Table 5:Distortion factor of Output Voltage of Chosen CMLI for various Values of Modulating Indices

DF	m_a				
	1.0	**0.9**	**0.8**	**0.7**	**0.6**
CO-1	0.202	0.342	0.606	0.999	1.102
VACO-1	1.395	1.412	1.403	1.304	1.171
CO-2	0.200	0.341	0.580	1.013	1.1006
VACO-2	1.378	1.430	1.390	1.301	1.2004
CO-3	0.207	0.314	0.571	1.004	1.132
VACO-3	1.395	1.390	1.390	1.290	1.169
CO-4	0.203	0.314	0.570	0.982	1.140
VACO-4	1.390	1.398	1.410	1.311	1.1614

5. CONCLUSION

In this paper various new schemes adopting the constant switching frequency and also variable switching frequency multicarrier control freedom degree combination concepts are developed and simulated for the chosen three phase CMLI. Performance indices like %THD, V_{RMS} (indicating the amount of DC bus utilization), CF, FF and DF related to power quality issues have been evaluated, presented and analyzed**.** Tables I and II show the THD and V_{RMS} respectively. Table III presents FF for all modulating indices. Tables IV and V display CF and DF for all chosen modulating indices. The result analyses indicate that appropriate PWM strategies have to be employed depending on the performance measure required in a particular application of MLI based on the criteria of output voltage quality (Peak value of the fundamental, THD and dominant harmonic components). The newly proposed variable amplitude carrier overlapping methods with less THD and higher RMS voltage can be implemented in industrial applications such as AC Power conditioners, static VAR compensators, drive systems, etc and in power generation industries.

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